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ADVANCED HYBRID NONMETALLIC COMPOSITE REINFORCEMENT FOR CONCRETE STRUCTURES

Vyacheslav Ruvimovich Falikman[a,*], Dmitry Anatolievich Ilyin[b], Valentina Fedorovna Stepanova[a]

[a] *Scientific Research Center "Construction"/Scientific Research Institute for Concrete and Reinforced Concrete, Department on Structural Concrete Durability, 2nd Institutskaya st., 6, 109428, Moscow, Russia*

[b] *Moscow State University of Civil Engineering (National Research University)/ Institute of Construction and Architecture, Department of Building Materials, Yaroslavskoye Shosse, 26, 129337, Moscow, Russia*

[*] corresponding author: vfalikman@yandex.ru

Abstract. During the last decades, fiber reinforced polymer (FRP) reinforcing bars for concrete structure has been extensively investigated and a number of FRP bars became commercially available. However, major shortcomings of the existing FRP bars are its low elastic modulus and high initial cost compared to conventional steel bars. The possibility to obtain a hybrid composite reinforcement (HCR) with increased performance based on glass and carbon fibers (GCFRP) is considered. The optimal content of carbon fibers in the amount of $6.3 - 6.5\,\%$ of the mass of the HCR was established. Further increase in the carbon fiber content gives a slight improvement in physical and technical characteristics, which is not comparable to the increase in the cost of the material. The manufacturing technology of HCR has been developed. The effect of hybridization on tensile properties of FRP bars were obtained by comparing the results of tensile test with those of non-hybrid GFRP bars. Operation regularities of HCR in the bent concrete beams are established. HCR can increase the stiffness of concrete beams by 15 % and crack resistance by 12 % in comparison with glass composite reinforcement. Dependences for predicting the HCR elasticity modulus are established. Physical and technical characteristics of HCR, including adhesion to concrete and resistance to the alkaline medium, were established. High durability of HCR for more than 50 years is experimentally shown. Experimental-industrial concrete piles, reinforced with GCFRP bars were produced and tested. For further development, new types of HCR, as well as a study of prestressed concrete structures are recommended.

Keywords: Durability, elasticity modulus, fiber reinforced polymer (FRP), glass and carbon fibers, hybrid composite reinforcement (HCR).

1. Introduction

The Russian industry for the production of composite polymer reinforcement (FRPR) is rapidly developing. Non-metallic reinforcements are becoming valuable alternatives for the classical concrete reinforcements [1]. This evolution started in the late eighties of last century. Having high tensile strength, low density, dielectric properties and high chemical resistance, FRPR is of great interest to builders and researchers. Composite materials of different type were introduced to overcome the inherent disadvantages of concrete: strength, durability, corrosion of steel rods, creep and shrinkage, flexibility and retrofitting aspects. Glass, aramid and carbon are the most popular fiber reinforcements, embedded in a pure polymer or in a polymer modified matrix. Material properties, reinforcement design, analysis and layout became important research topics, but practical applications came immediately after research, and sometimes even preceded research.

Along with the positive properties, FRPR has some disadvantages. Among them, it's necessary to mention a low modulus of elasticity and low heat resistance, increased creep under prolonged static load. All this hinders the widespread application of composite rebar in the construction practice.

Some of the above disadvantages could be eliminated when modifying the epoxy binder with nanoadditives. In the last decade, nanoparticles of various natures have been tested for modification of polymeric materials, wiz carbon nanotubes, fullerenes, astralenes, ultrafine diamond powders, nanodiamonds, montmorillonite, Aerosil, schungite, metal-containing nanocomposites, etc. [2–4]. The positive effect of the modification by copper and nickel nanoparticles was confirmed by one of the Russian FRPR manufacturers. They achieved stable increased physical and mechanical properties of the reinforcement and its high corrosion resistance [5].

However, the modification of the polymer binder is not enough to significantly increase the elastic modulus of the FRPR. This is due to the initial low modulus of elasticity of the glass fiber (70-80 GPa only). In turn, carbon fiber (CF) has a high modulus of elasticity (220 GPa), but the CFRP reinforcement is of 25-30 times more expensive.

The optimal solution may be a hybrid com-

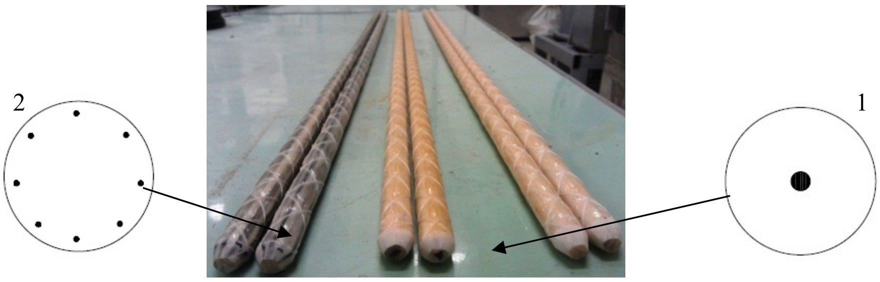


FIGURE 1. Experimental samples of FRPR; CF location.

Seq No.	Component	Kind	Quantity [%]
1	Fibreglass	JSC "Fiberglass"	71.3
2	Carbon fiber	AKSA A−49	3.7
3	Multicomponent epoxy binder	Solidifier−IMTHFA[1]	25
		Promoter−TDMAMPh[2]	25

[1] isomethyl tetrahydrophthalic anhydride
[2] 2, 4, 6−tris−(dimethylaminomethyl)−phenol

TABLE 1. Composition of HCR experimental samples

Designation	Nominal diameter d_n [mm]	Cross area [mm^2]	Density ρ [kg/m^3]	Tensile ultimate strength σ_B [MPa]	Elasticity modulus E_f [MPa]	Unit extension ε_B [%]	Bond resistance [MPa]
GFRP	11.89	111.03	2025	935	51500	1.72	11.92
ACC−C	11.98	112.72	2009	1115	59500	1.87	13.90
ACC−K	11.89	111.03	2046	1110	62000	1.60	12.76

TABLE 2. Test results

posite reinforcement (HCR) based on carbon and glass fibers, impregnated with a nanomodified epoxy binder. The use of two fiber types allows increasing of the elasticity modulus. Nanomodification of the epoxy binder provides high-quality joint work of the "fiber + binder" system. The result of this processing is a dense structure of the reinforcement, an inseparable relief from the bar, and a high proportion of reinforcing fiber.

2. Experimental and discussion

2.1. Making of HCR and its basic material properties

Previously, the hybrid effect was studied on the example of composite reinforcement made of glass and carbon fibers with their different locations. The authors noted that the final strain under tension of bars consisting of 37 % glass fibers and 23 % carbon fibers increased by 3 − 33 % compared to the carbon FRPR [6].

In the course of experimental work, a hybrid composite rebar (HCR) was manufactured and tested, in which 3.73 − 6.3 % of the glass fibers were replaced by CF with a modulus of elasticity of 220 GPa. At the same time, experimental and conventional samples of GFRP bars with a diameter of 12 mm were studied.

Samples of hybrid composite (HCR) and glass composite rebar (GFRP bar) were produced using industrial line. In experimental samples, 3.7 % of the glass fibers were replaced with CF. The theoretical value of the elasticity modulus of hybrid reinforcement calculated in accordance with Voigt's formula is 63.9 GPa. At the same time, two schemes were adopted for the location of the CF (Figure 1): 1−CF was concentrated in the center of the composite; the designation of this type of reinforcement is ACC−C; 2−CF were evenly distributed along the profile outline; the designation in this case is ACC−K.

Table 1 shows the ratio of hybrid composite reinforcement components. As the primary roving, optical fiber of JSC "Fiberglass" located in Gus Khrustalny was selected. Carbon fiber used was AKSA A-49 brand. Manufacture of FRPR was carried out according to the needletrusion technology [7].

The main performance characteristics of experimental samples according to GOST 31938-2012 are given in Table 2.

The rupture fracture pattern of the FRPR sample is shown in Figure 2a. The dependence of the strain on the stress (load) during the tensile test is shown in Figure 2b; it shows repeated peak stresses, which are explained by the hybrid effect.

The dependence of deformations on stress (load) during tests for axial expansion of ACC−K−10 samples with a carbon fiber content of 6.3 % is also characterized by repeated peak stresses, which indicates the pseudo-plastic behavior of combined composite reinforcement samples at break. The maximum strain of 1311 MPa is reached at 1.93 % deformation, after which the strain drops to 1200 MPa with a further rise to 1250 MPa. Then there is a breakage of the test sample ACC−K. The deformation reduction is occurred normally in accordance with the "mixtures law". The substitution of 6.3 % of glass fibers with carbon fibers resulted in an strength increase of the reinforcement by 17.4 % and the modulus of elasticity by 31.5 % compared to the samples of GFPR bars.

The quality of FRPR depends, first of all, on its components used in the production, viz fiber, multicomponent polymer binder, and their ratio in the matrix of the composite material. In addition, a significant role is played by production technology of FRPR, namely the tension force of the fiber, temperatures of polymerization of the binder, and cooling the finished product etc. Selecting of the optimal FRPR composition and the observance of technological processes allows obtaining a product with the specified parameters.

3. Corrosion (deterioration) resistance of HCR to alkaline environment

When achieving high physical and mechanical properties of FRPR, the determining factor becomes its corrosion (deterioration) resistance to aggressive media.

In Russian [8–12] and foreign [13–15] studies, the aggressive medium for composite polymer materials is usually taken as an alkaline medium, which is being characteristic for wet concrete. The aggressiveness of this medium is estimated by the pH value in the range of 12-14. To simulate the liquid environment of concrete, wet concrete may used directly [11]; aqueous NaOH solutions of various concentrations [10], saturated water solutions Ca(OH)2 with pH=13 [15] or pH=12 [14] may be used also. In order to accelerate the aggressive action of the alkaline medium on the material under study, the medium is heated to 50°C [14], 55°C [11], 70°C, 80°C [13], 100°C [8].

To date, however, there are no generally recognized theoretical dependencies that allow predicting the durability of the composite material on the basis of accelerated tests. Thus, according to the authors [13], 50 years of operation may be imitated by holding of the bar for 28 days in a saturated Ca(OH)2 solution with pH=13 at a temperature of 80°C. In [14], samples of FRPR were kept in a container with an alkaline medium at a temperature of 50°C for 52 weeks. The authors believe that 1 day under such conditions corresponds to 101 days under natural operating conditions. Test results show that the service life of the FRPR in concrete is about 100 years. In [15], tests were performed on FRPR samples placed in a saturated solution of Ca(OH)2 with pH=12 at a temperature of 50°C. Calculations made by authors show that 1 day of such exposure is comparable in intensity to more than 100−day alkaline exposure in concrete. Thus, the tested GFRP bars are able to serve in concrete for more than 47 years.

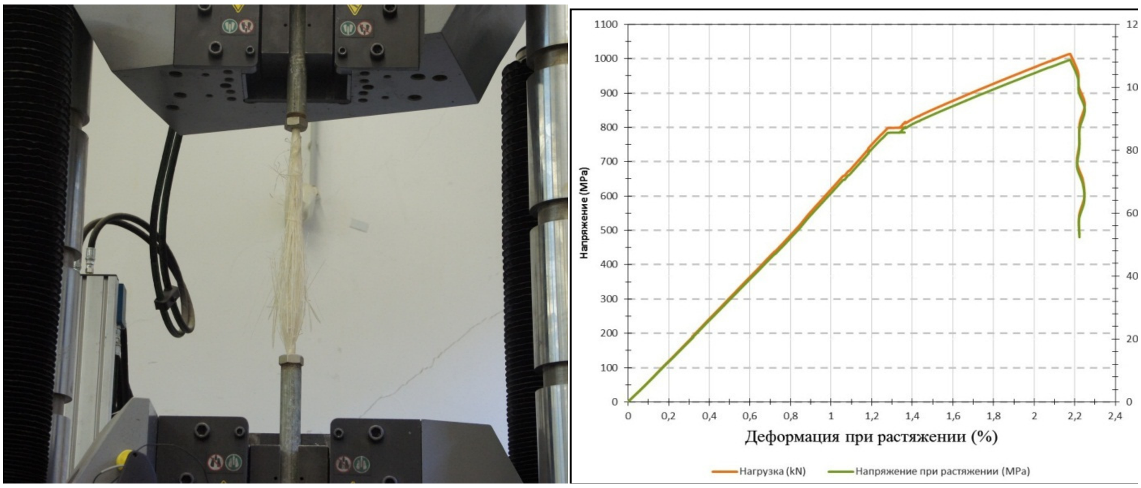
In this work, the assessment of the hybrid composite reinforcement (HCR) stability to the alkaline environment was carried out according to GOST 31938. Preliminary tests of the reinforcement for axial tension showed that the samples of HCR with the edge arrangement of carbon fibers, AKK-K series (Figure 1), more efficient than with the central placement, taking in account of elasticity modulus increasing. When replacing 3.7 % of glass fibers with carbon fibers, the modulus of elasticity was increased to 18 %. In this regard, samples of GFRP bars and ACC-K were studied.

An alkaline solution with a pH of 12.6−13 was used as an aggressive medium in the study, since this medium is the closest to the composition of the liquid concrete phase. The alkaline solution had the following composition: 8.0 g NaOH and 22.4 g KOH per 1 liter of distilled water.

The samples were immersed in an alkaline solution and kept in a closed container under a constant solution temperature of 60 ± 3 °C for 30 days, with only the middle section of the samples exposed to the alkaline environment; during the tests, the appearance of the samples was monitored before and after aging in an alkaline solution (Figure 3 a, b). The pH value of the solution was maintained in the range of 12.6−13.0 during the entire experiment. After exposure, tests were performed to determine the axial tensile strength in accordance with GOST 32492−2013. The results are presented in Table 3.

After aging in an alkaline environment, samples of FRPR are observed: rupture of the profile-forming thread, fading, and the appearance of «whitishness» (Figure 3). For GFRP samples, the rupture resistance decrease was by 5.2 %, for the AKK-K samples it was 5.6 %. The reduction of the elastic modulus was obtained by 2.31 % for GFRP samples and 1.26 % for ACC−C samples. Interstate standard GOST 31938-2012 did not specify an elastic modulus reduction of the FRPR after exposure to an alkaline environment. So, it seems reasonable to make provision for this limitation during next revision of GOST, as it was done in official edition for the strength degradation of the FRPR under axial tension.

Figure 4 shows samples of ACC−K tested for rupture after exposure to an alkaline medium. The samples were destroyed in the central part with a characteristic "fluff out" of the fibers.

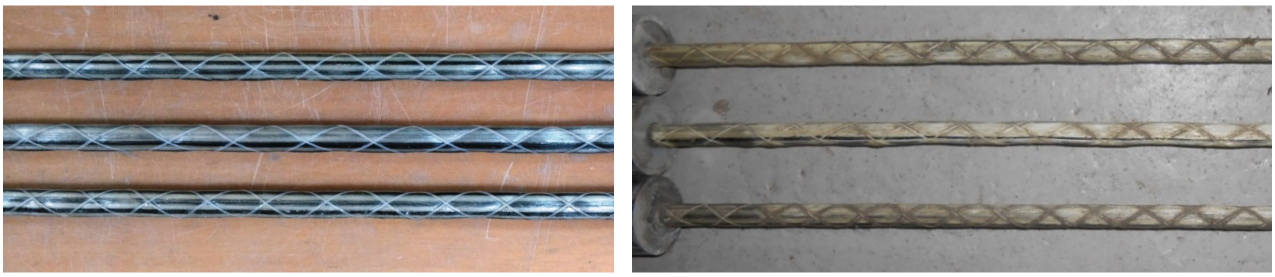


a) b)

Figure 2. FRPR tests. a) The nature of FRPR destruction at the break; b) Tensile stress-strain diagram.

Seq No.	Series FRPR	Ultimate tensile stress: reference value, unit value [MPa]	reference value, average value [MPa]	after exposure, unit value [MPa]	after exposure, average value [MPa]	Δ^1 [%]	Elasticity modulus, E_f: reference value, unit value [GPa]	reference value, average value [GPa]	after exposure, unit value [GPa]	after exposure, average value [GPa]	Δ^1 [%]
1	GFRP	935.5	935.1	861.8	886	5.2	52.7	53.20	50.7	52.0	2.31
2		943.6		844.5			55.1		53.4		
3		932.0		887.6			52.6		50.7		
4		938.1		879.0			54.7		51.0		
5		930.2		991.1			51.3		55.8		
6		931.4		853.2			52.8		50.2		
7	ACC−K	1080.1	1085.1	1040.4	1024	5.6	63.9	62.82	59.7	62.0	1.26
8		1100.2		992.3			62.3		61.3		
9		1050.4		1074.2			64.1		58.9		
10		1090.6		986.7			61.9		64.6		
11		1079.2		998.4			62.9		62.8		
12		1110.1		1052.4			61.8		64.9		

Table 3. FRPR strength under axial tension



a) b)

Figure 3. Appearance of ACC−K samples before (a) and after (b) exposure in an alkaline medium

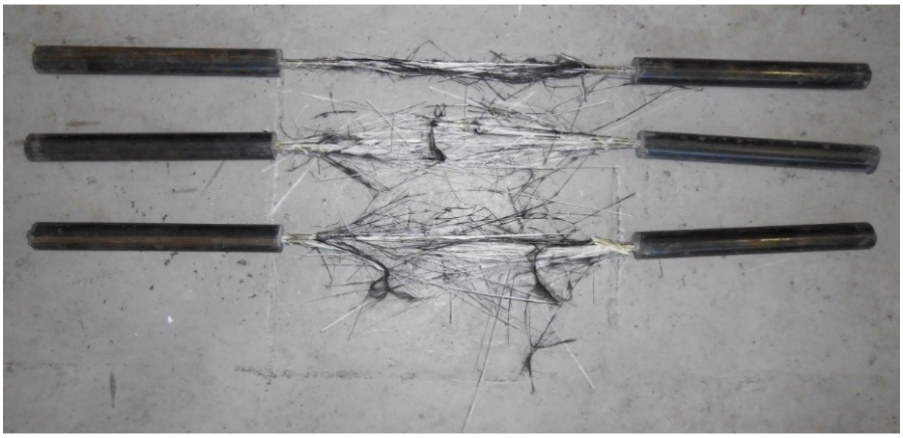


Figure 4. ACC−K samples after the rupture test

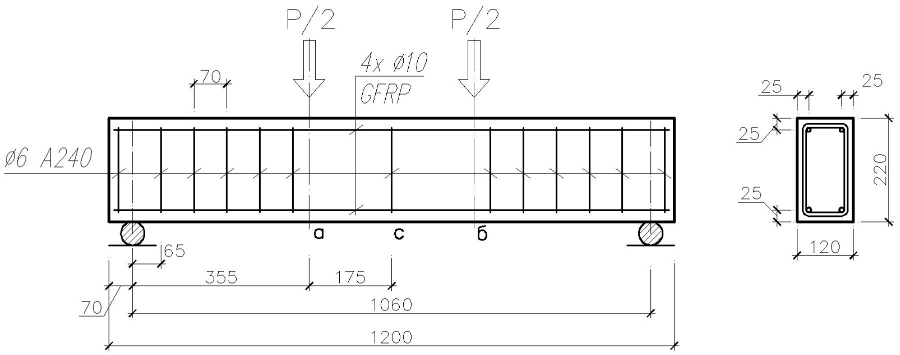


Figure 5. Concrete beam reinforcement diagram

3.1. Tests of concrete beams reinforced with HCR

To study a behavior of the HCR in concrete structures, beams were made with a cross section of $120 \times 220 \times 1200$ mm. Prototype beams were made of ordinary concrete (strength class B 20; cement grade CEM 1 42.5). As course aggregate, granite crushed stone was used (fraction of 5−25 mm); fine aggregate was quartz sand. Tests of control samples (concrete cubes) were carried out in accordance with GOST 10180.

The beams were tested for short-term action of bending moments in order to determine the maximum breaking moment, as well as to establish the nature of the collapse, the development of cracks, patterns of development of deflections, and deformations of concrete depending on the type of FRPR. The reference structures were reinforced with GFRP bars with a diameter of 10 mm (series B−1); experimental ones were reinforced with HCR having a diameter of 10 mm and a carbon fiber content of 6.3 % (series B−2−ACC). The reinforcement scheme for testing of both beams series was adopted the same according to Figure 5. Bent elements made of smooth steel reinforcement of class A240 with a diameter of 6 mm were used as clamps.

During the tests, the span between the supports was chosen of 106 cm; the distance from the supports to the point of the load application was 35.5 cm, and the distance between the clamps was accepted of 70 mm.

Deflections of concrete beams were measured with a digital deflection meter. According to the readings of the test machine sensors, the movements of the traverse were determined. Data were recorded after the application of the load at each stage.

Concrete deformations were recorded using a multichannel measuring system by Tokyo Sokki Kenkyujo Co., Ltd., Japan (TDS−530 model). As measuring instruments, conductive strain gauges with a polyester-based PL-60-11 type substrate with a measuring base length of 60 mm were used. Sensors were applied by a special technique to a pre-prepared concrete surface.

Measurements of concrete deformation and deflection of beams were carried out until the load-bearing capacity of the beams was exhausted.

The moment of crack formation and the kinetics of their development were controlled using a special template. The widths of normal cracks were fixed at the level of the stretched zone of the reinforcement, and inclined cracks - in the middle of the beam section. The length of the cracks was measured after testing by the marks applied to the beams. The testing process was accompanied by photography.

After the destruction of the beams, the destruction zone was fixed; the height of the cracks, the distance between the cracks, and the thickness of the concrete protective layer were measured.

The actual bearing capacity of the beams reinforced with GFRP bars and HCR was the same amounted to 89 kN, which is of 35 % higher than calculated for the ultimate limit state (ULS). For both series of beams, the destruction occurred along inclined sections with a rupture of the FRPR in the stretched zone.

For beams reinforced with GFRP bars, the first cracks formation occurred under a load of 15 kN, which is of 12 % less than the estimated moment of crack formation. In turn, in the beams with HCR, the first cracks were formed at a load of 17 kN, corresponding to the calculated load.

The normative crack opening width equal to 0.7 mm was formed in beams reinforced with HCR under a load of 37 % higher than in beams reinforced with GFRP bars.

The longitudinal deformation of compression and extension at height of normal beams section reinforced with a GFRP bars and HCR are linearly with the maximum compression strain at the upper edge and the maximum deformations at the lower edge. At the same time, the deformation of the lower stretched zone of the beams with GFRP bars at maximum load is of 70 % higher than the deformation of the beams with HCR.

The maximum deflections of beams reinforced with a HCR are of 15 % lower than the deflections of beams reinforced with GFRP reinforcement.

Tests of GFRP reinforcement for fire resistance according to Russian standards have shown that it is highly inflammable, but non-burning. When testing concrete structures reinforced with GFRP bars, even a short-term combustion occurrence does not occur. The structures are fireproof.

4. Conclusion

The paper deals with important material properties of FRPs, on which application and durability as reinforcement based.

Thus, a hybrid composite reinforcement based on glass and carbon fibers was produced, which is resistant to the alkaline concrete environment. When replacing 3.7 % of glass fibers with carbon fibers, the elastic modulus of the FRPR is increased to 18 %, and the elastic modulus remains high (62 GPa) even after exposure to an alkaline environment. Analysis of the deterioration nature of samples and test results showed that the edge location of the CF is the most effective. A large convergence of the theoretical (calculated) modulus of elasticity and the test results was achieved; the discrepancy limit does not exceed of 3 %. Theoretical calculations and tests have shown that the elastic modulus of the FRPR increases with an increase in the content of CF and with a decrease in the amount of polymer binder. At the same time, the feasibility of nanomodification of an epoxy binder with varying amounts of CF was proved. The decrease in the strength of the reinforcement in the axial tension of HCR after exposure to an alkaline environment is not key question, since its strength is not fully used in structure performance, and the value of reduction is within the requirements of GOST 31938. The analysis of research allows estimating the service life of HCR in concrete for about 50 years, which corresponds to known data. The regularities of operation of HCR based on glass and carbon fibers in bent concrete beams are established. It is shown that the HCR can increase the rigidity of concrete beams by 15 % and crack resistance by 12 % in comparison with GFRP reinforcement, and the elastic modulus remains high (62 GPa) even after exposure to an alkaline environment.

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