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The influence of cyclic freezing – thawing on the effectiveness of anchoring FRP reinforcement in concrete

Wpływ cyklicznego zamrażania i rozmrażania na efektywność zakotwienia zbrojenia FRP w betonie

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Abstract. The aim of the research work was to determine the influence of cyclic freezing and thawing on anchoring non-metallic BFRP and HFRP reinforcements in concrete beams. The analyses allowed confirmation of the analogy of the behavior of innovative HFRP bars in relation to the widely known BFRP bars. The values of slip for rebars subjected to cyclic freezing and thawing were an average of 50% greater than the values of slip recorded for those kept at constant temperature +20°C.

Keywords: non-metallic reinforcement; effectiveness of anchoring; thermal expansion; cyclic freezing and thawing.

Streszczenie. Celem badań było określenie wpływu cyklicznego zamrażania i rozmrażania na efektywność zakotwienia zbrojenia niemetalicznego BFRP i HFRP w belkach betonowych. Analizy pozwoliły na potwierdzenie identycznego zachowania się innowacyjnego zbrojenia HFRP w porównaniu z prętami BFRP. Wartości poślizgu prętów zbrojeniowych poddanych wpływowi cyklicznego zamrażania i rozmrażania były średnio o 50% większe niż prętów utrzymywanych w stałej temperaturze +20°C.

Słowa kluczowe: zbrojenie niemetaliczne; efektywność zakotwienia; rozszerzalność termiczna; cykliczne zamrażanie i rozmrażanie.

FRP reinforcing bars are characterised by a higher coefficient of thermal expansion CTE than concrete. In case of composite materials, it is necessary to distinguish coefficient values in transverse direction, dependent primarily on attributes of the polymer matrix, and longitudinal direction LCTE *(Longitudinal Coefficient of Thermal Expansion)*, which is determined mainly by fiber properties. Values of TCTE coefficients for AFRP bars *(Aramid Fiber Reinforced Polymer)* are 8 times, and in case of CFRP *(Carbon Fiber Reinforced Polymer)* and GFRP *(Glass Fiber Reinforced Polymer)* rebars, 3 times greater than the value of thermal expansion coefficient of concrete [1]. Under the influence of cyclic freezing and thawing, composite reinforcement located inside concrete elements will be deformed more than the concrete surrounding it. This, in consequence, results in emergence of tension and microspaces in the areas of contact between both materials. The phenomenon described above might result in decrease of anchoring between reinforcement and concrete, leading to premature loss of load-bearing capacity of concrete elements [2, 3]. Majority of research works covering the topic of thermal expansion of non-metallic reinforcement described the behavior of GFRP, CFRP or AFRP bars under the influence of changing temperature [3, 4], whereas only a few works discussed BFRP *(Basalt Fiber Reinforced Polymer)*, what became the reason for conducting the experiments described in the article.

The research program included the determination of values of coefficient of longitudinal (LCTE) and transverse (TCTE) thermal expansion as well as testing the effectiveness of anchoring of BFRP and HFRP *(Hybrid Fiber Reinforced Polymer)* composite reinforcement in concrete. The aim of the above was to define the impact of cyclic freezing and thawing on the effectiveness of anchoring of basalt and hybrid (composed of carbon and basalt fibers) reinforcing bars in concrete.

Procedure for determining the coefficient of thermal expansion

The test procedure for longitudinal (LCTE) and transverse (TCTE) coefficient of thermal expansion of composite rods consisted of placing a straight section of BFRP and HFRP bars with a length of 250 mm in a specifically designed steel supporting frame and application of two opposite pairs of dial gauges having a measurement accuracy of 0,001 mm and range of 1,0 mm (figure 1). The samples were simply rested on two supports and their position was stabilized by stylus tip force of the sensors. In order to increase the accuracy of measurements and to avoid accidental slippage of sensors from irregular surface of rebars, two metal plates with dimensions of 20 x 20 x 2 mm were glued to the projected measurement points.

The subject of the research were BFRP and HFRP reinforcing bars made on the basis of epoxy resin matrix with carcass made of basalt and mixed fibers (75% basalt fibers and 25% carbon fibers). Three reinforcing rods with

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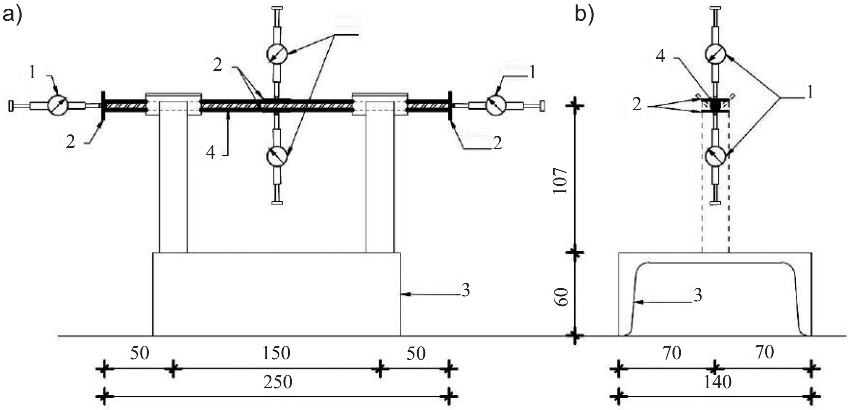

Fig. 1. Scheme of a test stand for testing longitudinal and transverse thermal expansion of composite bars: a) side view; b) cross-section; 1 – dial indicators; 2 – steel plates; 3 – support frame; 4 – composite bars 250 mm long. All dimensions are in mm

Rys. 1. Schemat stanowiska do badania podłużnej i poprzecznej rozszerzalności termicznej prętów kompozytowych; a) widok z boku; b) przekrój; 1 – czujniki zegarowe; 2 – naklejane stalowe blaszki; 3 – rama podporowa; 4 – pręty kompozytowe o długości 250 mm. Wszystkie wymiary podano w mm

diameter of 4, 6 and 8 mm were used in the experiment.

First, the entire presented system was placed inside a freezing chamber and reference data was collected from four dial gauges at the temperature of +20°C. Next, the chamber was launched and set to three cycles of freezing/thawing at the temperature ranging from -20°C to +20°C, each lasting for 8 hours. 5 measurements of expansion change at the temperature of -20°C and +20°C were made for every analysed reinforcing bar type. The obtained results were compared with the length of test samples and presented in the table in the form of LCTE and TCTE coefficients of thermal expansion [10-6/°C].

Average values of longitudinal (LCTE) and transverse (TCTE) thermal expansion coefficients and standard deviation (σ) values for BFRP and HFRP reinforcement

Wartości współczynników rozszerzalności termicznej podłużnej (LCTE) i poprzecznej (TCTE) oraz odchylenia standardowego (σ) w przypadku zbrojenia BFRP i HFRP

Rodzaj pręta	Średnica [mm]	LCTE (σ) [10^{-6}/°C]		TCTE (σ) [10^{-6}/°C]	
BFRP	4,0	1,4 (0,2)	1,5 (0,2)	38,8 (2,3)	37,8 (2,1)
	6,0	1,7 (0,2)		36,5 (2,5)	
	8,0	1,5 (0,3)		38,2 (1,4)	
HFRP	4,0	1,7 (0,2)	1,4 (0,2)	32,6 (2,5)	33,5 (2,0)
	6,0	1,0 (0,2)		34,2 (2,9)	
	8,0	1,5 (0,2)		33,7 (0,4)	

Procedure for testing the effectiveness of bar anchoring

The sample for testing the efficiency of bar anchoring comprised of two concrete beams connected by a steel joint and sharing one reinforcing bar as shown in figure 2. Dimensions of the beams corresponded with the samples of reinforcing bars with a diameter up to 16 mm acc. to RILEM Recommendations [7].

A simply supported beam loaded with two symmetrical forces was examined. The length of bar embedment in concrete was 10 times its diameter. The remaining sections of the bar were encased in sleeves securing it from contact with concrete and allowing it to move freely along its axis. At the ends of rebars exceeding the outline of beams, sensors were placed to measure the slippage of reinforcement with an accuracy of 0,001 mm and a range of 30 mm. It was necessary to prepare special forms enabling centric placement of reinforcing bars and steel construction reinforcement preventing the concrete elements from splitting (photograph). Concrete C30/C37, meeting the requirements for concrete used in XF3 exposure class according to PN-EN 206+A1:2016-12 [8], was used for testing.

A total of 12 series of beams were made using BFRP and HFRP rebars with a diameter of 4, 6 and 8 mm, which were varied in terms of conditioning methods. First, all samples were seasoned for 28 days in water at +20°C. Subsequently, 6 series of samples were placed in a freezing chamber at the controlled variable temperature and subjected to 150 cycles of freezing and thawing at the temperature ranging from -20°C to +20°C, imitating a fifty-year period of use in case where the elements are in the area of variable water level or thawing agents acc. to PN-B_06265:2018-10 standard [9]. The remaining 6 series of samples were put in an air-conditioned room with a constant temperature of +20°C and air humidity at 40%. All samples were stored in a room with a constant temperature of +20°C for 24 hours in order to prepare them for destructive tests. Beams were examined at a constant temperature of +20°C.

The spacing between supports in the testing machine was 650 mm. The loads were applied by means of two steel rolls spaced apart by 200 mm (figure 2). Loads were applied in stages, detaining their increase and stabilizing their levels after reaching determined stress values in rebars every 80 MPa. On the basis of formulas presented in PN-EN 10080:2007 [10], it was calculated how much force was required to be applied to the spreader beam to achieve theoretical stress values in FRP rebars at 80, 160, 240 MPa etc. until destruction of the beam. The load was consequently increased until failure of the tested element. Each stage of load application was completed in 30 seconds. Loading with force of a constant value at a given stage did not exceed 120 seconds. Measurements of slip of reinforcing bars were taken once the readings had stabilized on both dial sensors.

During the test, values of the forces accompanying the slippage of rebars equal to 0,01, 0,1, 1 mm and the value of maximum achieved destructive force were registered. The trial ended after complete loss of grip of the tested

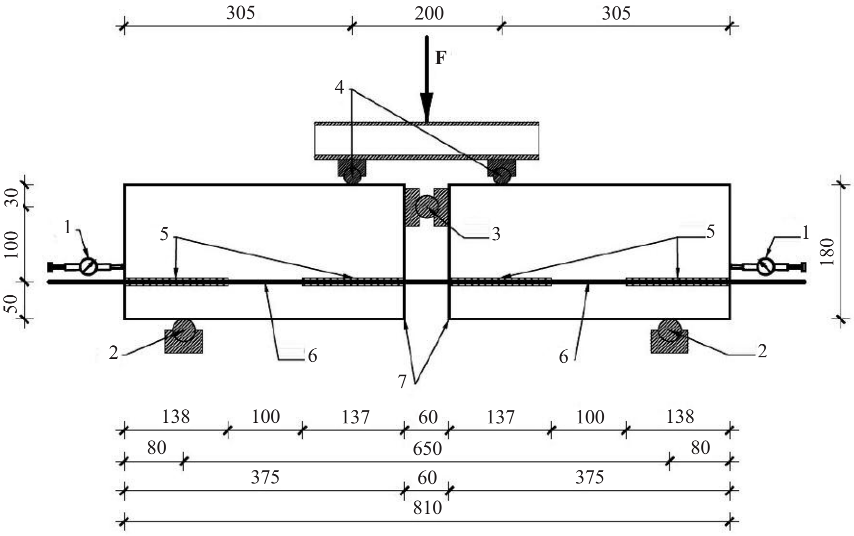

Fig. 2. Arrangement for testing the efficiency of bar anchoring: 1 – dial indicators; 2 – supports; 3 – steel joint; 4 – load rollers; 5 – aluminum shielded tubes; 6 – anchoring zone of FRP bars (length of 10 × Ø) with diameter 4 ÷ 8 mm; 7 – concrete beams. All dimensions are in mm

Rys. 2. Schemat stanowiska do badania efektywności zakotwienia prętów: 1 – czujniki zegarowe; 2 – podpory przegubowe; 3 – przegub stalowy; 4 – rolki obciążeniowe; 5 – osłonowe rurki aluminiowe; 6 – strefa zakotwienia prętów FRP (długość 10 × Ø) o średnicy 4 ÷ 8 mm; 7 – belki betonowe. Wszystkie wymiary podano w mm

Sample reinforcement during assembly in the mol. Only the central composite bar is routed through the mold walls. The other holes are mounting holes for screws

Zbrojenie próbki w trakcie montażu w formie. Jedynie centralny pręt kompozytowy jest przeprowadzany przez ściany formy. Pozostałe otwory, to otwory montażowe na śruby

reinforcing rods in both parts of the samples or upon rupture of the composite reinforcing bars. In case a slip of value greater than 3,0 mm was observed at one end of the beam, the anchoring of the reinforcement bar was strengthened in order to prevent further displacement and the test was continued until the connection failed in the remaining part of the sample. Stabilization was performed with the use of a steel clamp of appropriate length with screws and quick-drying glue fitted at the end of the beam.

Results of the research

The obtained values of coefficients of thermal expansion of basalt and hybrid reinforcing bars were corresponding with a typical range of coefficient values for rods based on carbon and glass fibers. The research has shown that HFRP bars are characterized by a 14% lower TCTE coefficient value and a 6,7% lower LCTE coefficient value than BFRP reinforcing bars. This is due to the influence of 25% carbon fiber content in hybrid rebars. According to the data presented in [1], samples based on CFRP fibers demonstrated lower values of thermal expansion coefficient than samples based on BFRP fibers achieved in the conducted tests.

Beams subjected to cycling freezing/thawing were marked as FT, whereas the beams conditioned at a constant temperature were tagged as REF. Values of slip of bars in relation to applied load is presented on figure 3. Destructive impact of cycling freezing and thawing on durability of the concrete – composite bar junction was found through comparison of slip of FRP rebars at different levels of beam loading. BFRP FT series demonstrated greater slippage of rebars (by an average of 51%) than BFRP REF series. Similarly, HFRP FT series were characterized by an average of 48% greater slip of rebars than HFRP REF series.

Adhesive stress values for all series of bars with a slip of 0,01, 0,1 and 1,0 m were similar. In the range of 0 ÷ 20% maximum load, no significant rebar slip values were noticed At 20% of maximum stress, a rapid increase in slip values was observed. At over 40% of maximum stress, the graph of slip values growth had a linear course until the moment of failure of the samples.

The target failure criterion for all tested elements was rupture of composite bars. In none of the samples did the reinforcement completely slide

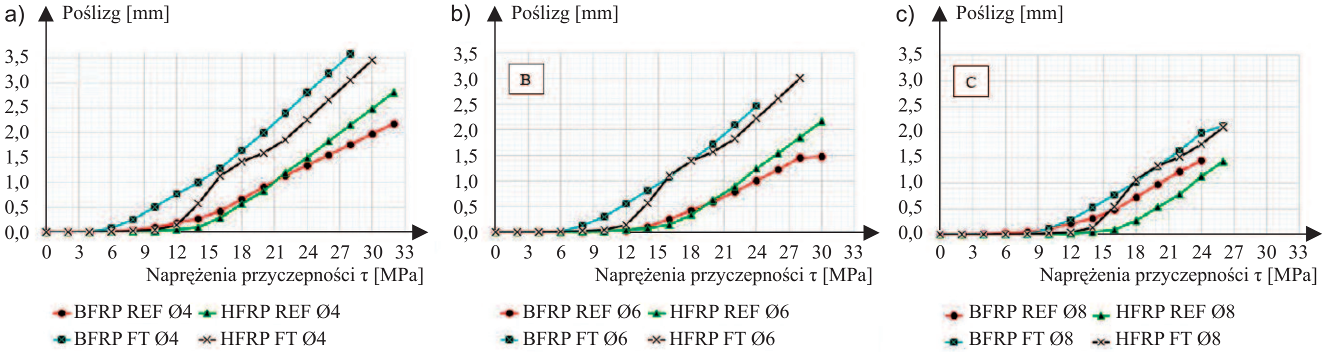

Fig. 3. Average values of bar slips [mm] depending on the value of adhesion stress [MPa] for bars with diameters of: a) 4 mm; b) 6 mm; c) 8 mm

Rys. 3. Średnie wartości poślizgu prętów [mm] w zależności od wartości naprężeń przyczepności [MPa] w przypadku prętów o średnicy: a) 4 mm; b) 6 mm; c) 8 mm

out of the concrete beam. The maximum achieved stress levels in rebars were, approximately, corresponding with the predicted values of tensile strength. Beams from the FT series were destroyed at on average by 10% less force than beams from the REF series. This means that the greatest impact on reducing the durability of concrete elements reinforced with composite bars has the degradation of concrete-composite junction. Moreover, the research confirmed the similar slip values for BFRP and HFRP bars in concrete. The external appearance of both types of rods was near identical, so they were not distinguishable to the naked eye. Even the exposure of bars to cyclic freezing and thawing did allow to detect any difference in the level of their degradation.

Conclusions

During the experiment, the physical properties of composite rods made of basalt fibers (BFRP) and basalt and carbon fibers (HFRP) were determined in variable temperature conditions from -20°C to +20°C. HFRP rods have lower coefficients of thermal expansion LCTE and TCTE by 6.7% and 11.4%, respectively, compared to BFRP rods. This was influenced by the 25% carbon fiber content in the hybrid bars. The TCTE values of FRP bars obtained from the tests are three times higher than the TCTE values corresponding to steel bars described in, among others, [1].

The efficiency of anchoring BFRP and HFRP bars conditioned at a constant temperature of +20°C and cyclically frozen and thawed at temperatures from -20°C to +20°C was assessed and compared.

The degradation of the concrete-composite bar junction has a significant impact on reducing the durability of concrete elements reinforced with composite bars. This is the effect of, among others, a significant difference between the values of thermal expansion coefficient of concrete (10×10^{-6}/°C) and FRP rods ($1,4 \div 37,8\times10^{-6}$/°C). Reinforcing bars subjected to cyclic freezing and thawing demonstrated on average 50% higher slip values than those kept at a constant positive temperature. This indicates a decrease in anchoring efficiency of the elements used for a long time at cyclically variable (positive and negative) temperature. Therefore, it is necessary to consider increasing the required anchoring length of elements exposed to the XF3 environment by 50% according to [10] compared to elements protected from unfavorable temperatures.

In terms of anchorage efficiency, durability, appearance or degree of surface degradation of the bars, no significant difference was found between BFRP and HFRP reinforcement.

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