TECHNICAL TRANSACTIONS 7/2017
CZASOPISMO TECHNICZNE 7/2017
CIVIL ENGINEERING
DOI: 10.4467/2353737XCT.17.107.6648

Krzysztof Ostrowski (kostrow@agh.edu.pl)
Faculty of Mining and Geoengineering, AGH University of Science and Technology

The influence of CFRP sheets on the strength of specimens produced using normal concrete and high-performance concrete assessed using uniaxial compression tests

Wpływ włókien węglowych na wytrzymałość próbek z betonu zwykłego i wysokowartościowego ściskanych jednoosiowo

Abstract

This article presents the results of an experimental investigation on the influence of carbon-fibre-reinforced polymer (CFRP) sheets on the strength of short concrete columns constructed from normal concrete (NC) and high-performance concrete (HPC). The results show that external confinement can significantly improve the ultimate strength and strain of the specimens. The stress-strain response of confined concrete depends largely on the type of concrete with regard to its compressive strength. The results demonstrate that composite columns constructed from normal concrete work in an elastic-plastic range with strengthening, whereas strengthening of columns constructed from high-performance concrete did not occur. The study indicates that the confinement .

Keywords: composite column, normal concrete, high-performance concrete, carbon reinforced polymer material, stress-strain

Streszczenie

W artykule przedstawiono rezultaty eksperymentalnych badań poświęconych wpływowi mat z włókien węglowych na wytrzymałość krótkich kolumn betonowych wyprodukowanych z betonu zwykłego i wysokowytrzymałościowego. Wyniki wskazują, iż stosowanie CFRP może w znaczący sposób zwiększyć wytrzymałość i odkształcalność próbek. Charakterystyka naprężenie-odkształcenie wzmocnionych kolumn zależy w istotny sposób od wytrzymałości betonu. Wyniki przeprowadzonych badań wskazują na sprężysto-plastyczną ze wzmocnieniem charakterystykę pracy wzmocnionych kolumn z betonu zwykłego, w przeciwieństwie do betonu wysokowartościowego, gdzie wzmocnienie nie występuje. Badania wskazują, iż efektywność wzmocnienia kolumn zespolonych spada wraz ze wzrostem wytrzymałości na ściskanie rdzenia betonowego.

Słowa kluczowe: słup zespolony, beton zwykły, beton wysokowytrzymałościowy włókna węglowe, naprężenie–odkształcenie.

1. Introduction

With recent advances in composite materials technology, fibre-reinforced polymers (FRP) have reached a new level in the field of civil engineering to repair and retrofit existing infrastructures or to design new infrastructures [2].

Retrofitting of concrete columns using FRP jackets with fibres predominately oriented in the hoop direction has become popular within the structural engineering community [5]. FRP-confinement could increase both the compressive strength and the ultimate strain of concrete columns [6, 7]. The confinement of concrete columns is thus an application where the external wrapping by glass- or carbon-fibre-reinforced polymers is particularly effective [1]. CFRP has high strength and a high Young's modulus, it has good resistance to aggressive environments, a high strength-to-weight ratio and good fatigue properties [8].

Epoxy resins are most commonly used in strengthening by FRP – these resins are examples of organic polymer matrices. Epoxy resins have disadvantages including: their fairly high costs; the hazards they pose for the manual worker; their incongruity at low temperatures or with humid surfaces; their lack of permeability to vapour, the obstacle they pose when assessing the post-earthquake damage of reinforced concrete behind (intact) composite jackets; their weak performance in high-temperature conditions. Besides epoxy resin, it is possible to use inorganic matrices – these are more adaptable, more cost-effective – they are eco-friendly substitutes for epoxy resin and the efficiency of the bond between the concrete surface and the cement-based composites in confined mode is acceptable [12,13].

The use of CFRP sheets can be of significant importance for the strengthening of historical buildings and monuments where change of use is considered as this often causes an increase in loads. The many historical buildings were often constructed from low-performance concrete which corresponds to the current C15/20 class. Strengthening with CFRP confinement can increase the bearing capacity of a construction and the maximum strains [10].

For more than twenty years, high-performance concrete has been increasingly applied in structural engineering due to its superior material properties related to strength, stiffness, and durability. One of its major drawbacks is that the ductility of HPC generally decreases as compressive strength increases. High strength concrete structural members therefore generally exhibit a lack of ductile behaviour and hence brittle failure. Using CFRP can be an effective method for improving the ductility of confined concrete columns constructed from HSC [3].

This article is based on selected results of the author's work [9, 10] on the basis of which, a comparative analysis of the influence of CFRP sheets on the strength of the specimens produced by normal concrete and high-performance concrete was performed.

2. Experimental programme

The specimens and materials

In total, twelve specimens were analysed covering two different concrete mixtures (NC – normal concrete and HPC – high-performance concrete). All specimens were manufactured in a local laboratory and tested under uniaxial compression. The mix design of each mixture is displayed in Table 1. In this study, the constituent materials making up the concrete mixtures were as follows: Portland-fly ash cement type I – CEM I 42.5R (in case of HPC); Portland-fly ash cement type II – CEM II/B-V 32.5R (in case of NC) [16]. SikaFume was used as a concrete additive in fine-powder form based on silica fume technology [15]. Sika ViscoCrete-5-600 was used as a superplasticiser. Diabase (ϕ2–8) and fine sand (ϕ0–2) were used as aggregate.

Six samples were made of each type of concrete. All specimens were divided into four groups: normal concrete columns (NCC); high-performance concrete columns (HPCC); normal concrete columns reinforced with CFRP (NCC-CFRP); high-performance concrete columns reinforced with CFRP (HPCC-CFRP). Each of these groups was represented by three samples.

The specimens had a 150mm diameter and were 400mm in height. The concrete specimens were ripened in a water bath at a temperature of 20°C for twenty-eight days.

Table 1. Proportions of concrete mixture ingredients

Mix type	Cement [kg/m^3]	Sand [kg/m^3]	Coarse aggregate [kg/m^3]	Water [kg/m^3]	SikaFume [kg/m^3]	Superplasticiser [kg/m^3]	w/c ratio [-]
NC	366	942	942	183	–	–	0.5
HPC	500	650	1000	200	60	10	0.4

Preparation of specimens

After the maturation of the samples in the water bath, they were dried out for seven days. The efficiency of the CFRP confinement depends on the preparation of the concrete surface before the lamination process. To ensure adequate bond strength in this study, the concrete surface was sanded, cleaned and dried. The concrete surface before and after the sandblasting process in the case of HPC is shown in Fig. 1. As a result of adding a superplasticizer and SikaFume to the concrete mixture, the concrete surface was very tight and glassy. This surface provides a very weak level of adhesion to the epoxy resin and prevents its penetration into the concrete. This is why it is so important to emphasise the proper preparation of the resin-concrete contact surface.

According to the resin manufacturer, the moisture content of the concrete surface should be approximately 5% – this condition was satisfied. The confined cylinders were wrapped with Sikawrap301c carbon fibres by using Sikadur330 epoxy resin using the manual dry layup process. In all cases, the principal fibres were oriented perpendicular to the column axis, in a so-called 0° orientation. The fibre sheets were overlapped by 150 mm. The age of

Fig. 1. The concrete surface before (left) and after sandblasting process (right) in the case of HPC

the concrete specimens at the moment of testing was six weeks. The strength parameters of Sikawrap301c and Sikadur330 were in accordance with the manufacturer's specifications as shown in Tables 2 and 3, respectively.

Table 2. Characteristic parameters of Sikawrap301c [15]

Areal Weight	304 g/m^2 ± 10 g/m^2	
Fabric Design Thickness	0.17 mm (based on carbon content)	
Fibre Density	1.80 g/cm^3	
Dry Fibre Properties	Tensile E-modulus	230 000 MPa (nominal)
	Tensile strength	4 900 MPa (nominal)
	Elongation at the break	2.1% (nominal)

Table 3. Characteristic parameters of Sikadur330 epoxy resin [15]

Density	Mixed resin: 1.3 ± 0.1 kg/dm^3 (at + 23°C)			
Tensile Strength	30 MPa (7 days at + 23°C)			(PN-EN ISO 527-3)
Bond Strength	Concrete fracture (> 4 N/mm2) on sandblasted substrate:			(PN-EN ISO 4624)
E-Modulus	Flexural:	3 800 MPa	(7 days at + 23°C)	(PN-EN 1465)
	Tensile:	4 500 MPa	(7 days at + 23°C)	(PN-EN ISO 527-3)
Elongation at Break	0.9% (7 days at + 23°C)			(PN-EN ISO 527-3)

Instrumentation and loading conditions

Specimens were loaded under a monotonic uniaxial compression loading. The tests were performed using a servo-controlled MTS Rock and Concrete Mechanics Testing System. The load was applied at a quasi-static displacement rate of 5×10^{-5} [s^{-1}]. The measurement of the axial force was carried out by means of a force transducer and the displacements were measured using linear variable differential transformer (LVDT) sensors. Radial and axial displacements were determined through the measurement of the whole columns' dimension changes, where the LVDT sensors were mounted directly between compression plates (Fig. 2).

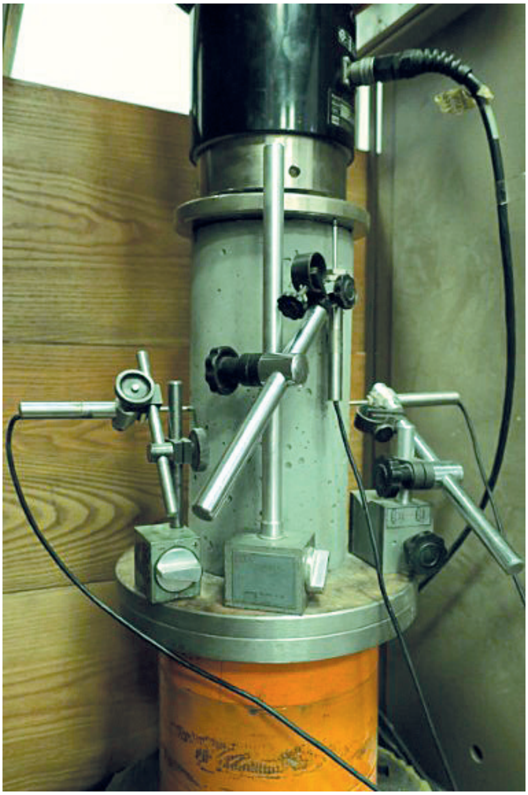

Fig. 2. Measurement system for specimens

3. Results and discussion

The test results described in Table 4 show that CFRP confinement can significantly enhance the specimens' ultimate strengths and strains. All the CFRP confined specimens failed due to the hoop tensile rupture of the CFRP jacket in the weakest location of the specimen, with a sudden explosive noise. Figs. 3 & 4 show the typical failure modes of both the unconfined and the confined specimens.

Table 4. Experimental results

Specimen	Ultimate load [kN]	Nominal compressive strength [MPa]	Axial strain during fracture of columns [‰]	Axial strain during fracture of concrete [‰]	Transverse strain during fracture of concrete [‰]	Modulus of elasticity E_1 [GPa]	Modulus of elasticity E_2 [GPa]
Normal Concrete Columns							
NCC1	520	30.25	3.95	3.95	1.04	8.52	–
NCC2	622	35.69	3.73	3.73	1.98	12.20	–
NCC3	517	29.28	3.78	3.78	3.77	10.12	–
High-Performance Concrete Columns							
HPCC1	1312	74.25	4.29	4.29	3.50	17.42	–
HPCC2	1115	63.12	4.40	4.40	3.85	13.48	–
HPCC3	1000	57.36	4.79	4.79	3.81	14.97	–
Normal Concrete Columns reinforced with CFRP							
NCC-CFRP1	1290	72.99	25.69	5.44	2.75	12.72	1.36
NCC-CFRP2	1255	71.97	25.21	6.34	4.11	10.30	1.36
NCC-CFRP3	1236	71.87	22.86	5.01	3.57	14.40	1.40
High-Performance Concrete Columns reinforced with CFRP							
HPCC-CFRP1	1414	80.04	6.16	–	–	16.46	–
HPCC-CFRP2	1635	92.50	5.17	–	–	22.58	–
HPCC-CFRP3	1515	85.70	5.52	–	–	18.09	–
Summary							
Group of specimens	Average compressive strength [MPa]	Standard deviation of the mean [MPa]	Average axial strain during fracture of columns [‰]	Average axial strain during fracture of concrete [‰]	Average transverse strain during fracture of concrete [‰]	Average modulus of elasticity E_1 [GPa]	Average modulus of elasticity E_2 [GPa]
NCC	31.74	2.63	3.82	3.82	2.26	10.28	–
HPCC	64.91	7.01	4.68	4.68	3.72	15.29	–
NCC-CFRP	72.28	0.48	24.59	5.60	3.48	12.47	1.37
HPCC-CFRP	86.08	4.28	5.62	–	–	19.04	–

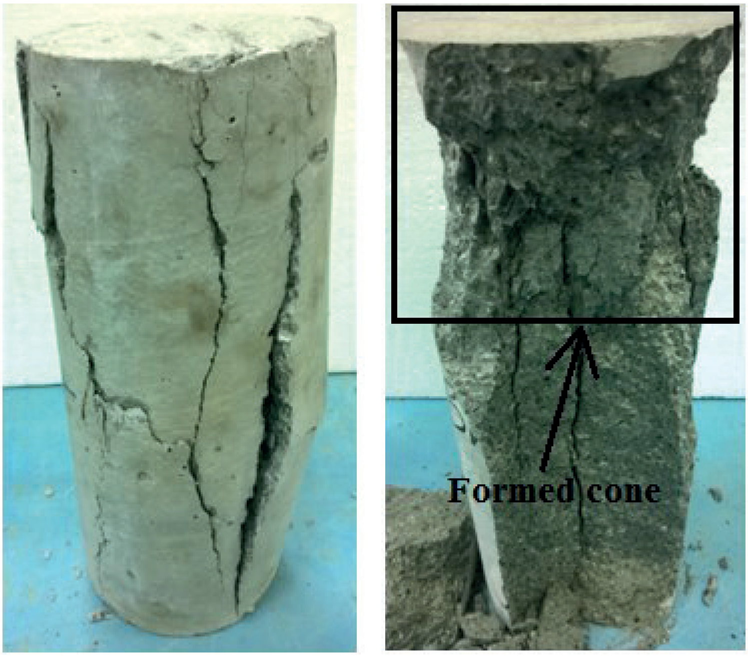

Fig. 3. Failure modes of NCC (left) and HPCC (right)

Fig. 4. Failure modes of NCC-CFRP (left) and HPCC-CFRP (right)

Axial stress–strain response

The experimental axial stress-axial strain and axial stress-lateral strain curves of CFRP-confined columns are shown in Figure 5. The nominal axial stresses were defined by dividing the axial loads by the total cross-sectional areas of the columns – the small thickness of the CFRP was insignificant in this evaluation. The modulus of elasticity E1 and E2 were calculated without preloading cycles; therefore the results are qualitative. The modulus of elasticity E1 and E2 were identified in the range of stress ranging from 15% to 33% [4] and from 75% to 95% value of maximum stress, respectively. The point of inflection on the stress-strain curve was the moment of determination of the axial and transverse strains during the fracture of concrete in the case of CFRP columns.

The average compressive strength of NCC is 31.74 MPa; standard deviation in this case is 2.63 MPa. The average longitudinal and transverse strains of NCC at the time of destruction

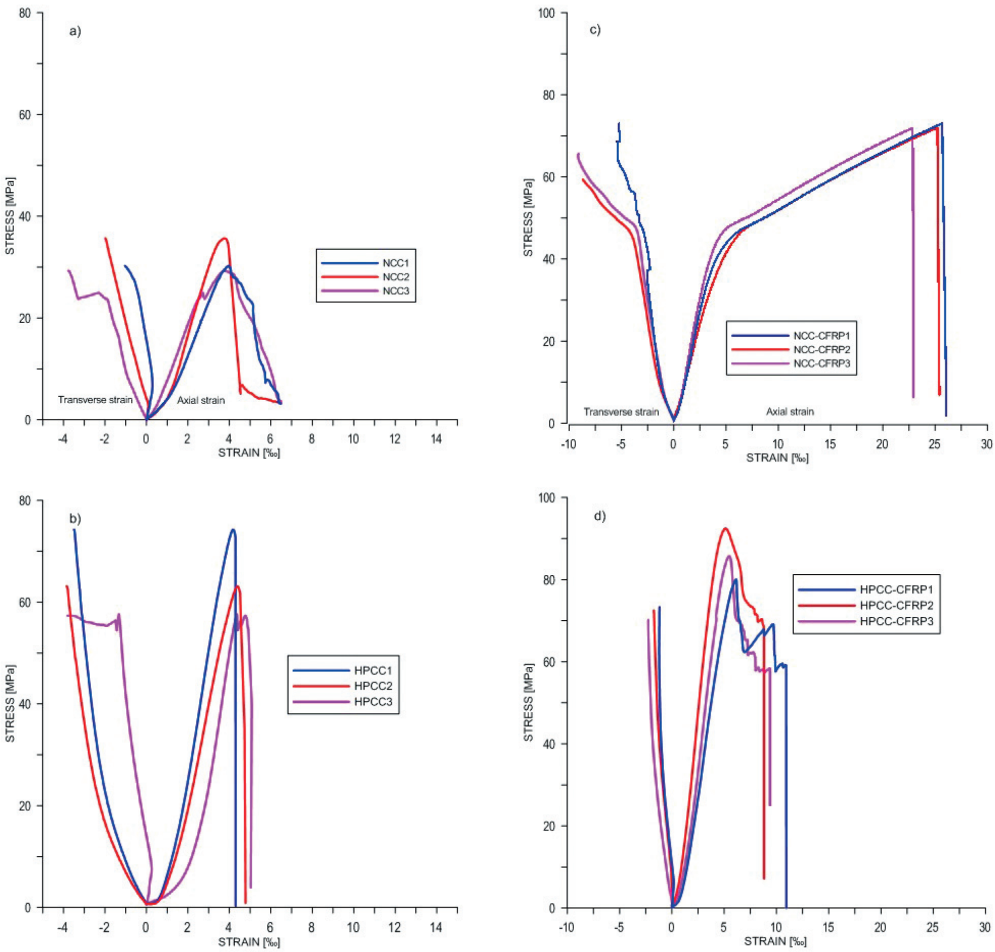

Fig. 5. Axial stress–strain relationships for specimens:
NCC (a), HPCC (b), NCC-CFRP c), HPCC-CFRP (d)

were 3.82‰ and 2.26‰, respectively. The average modulus of elasticity E_1 is 10.28 GPa. The average compressive strength after retrofitting with CFRP increases by 128%. The average maximum axial strains in the case of NCC-CFRP are 24.59‰, the modulus of elasticity E_1 is 12.47 GPa. It is worth noting the standard deviation, which is a mere 0.48 MPa. The modulus of elasticity E_2 is 1.37 GPa. The NCC-CFRP columns may be treated as a composite material working as elastic-plastic with strengthening.

The average compressive strength of HPCC is 64.91 MPa; standard deviation in this case is 7.01 MPa. The average longitudinal and transverse strains of HPCC at the time of destruction were 4.68 ‰ and 3.72‰, respectively. The average modulus of elasticity E_1 is 15.29 GPa. The use of CFRP sheets in the covering of HPCC increases the compressive strength and axial strain by 33% and 20% respectively. The modulus of elasticity E_1 for HPCC-CFRP is 19.04 GPa. The behaviour of HPCC-CFRP is close to being linearly elastic. After exceeding the load capacity, we observe a step loss of stiffness leading to the destruction of the element – this is not observed in the case of NCC-CFRP.

Adhesion of CFRP confinement to the concrete surface

The aspect of the resin-concrete contact area is often overlooked in the interpretation of the test results. It is, however, a very significant role in determining the performance of CFRP, especially in the new generation of concrete, in which the surface is specific and different from normal concrete. Figure 6 shows the laminate which was breaking away from the normal concrete (left) and the high-performance concrete (right). We can observe that the Sikadur330 epoxy resin thoroughly adhered to the concrete surface of NC. The coarse

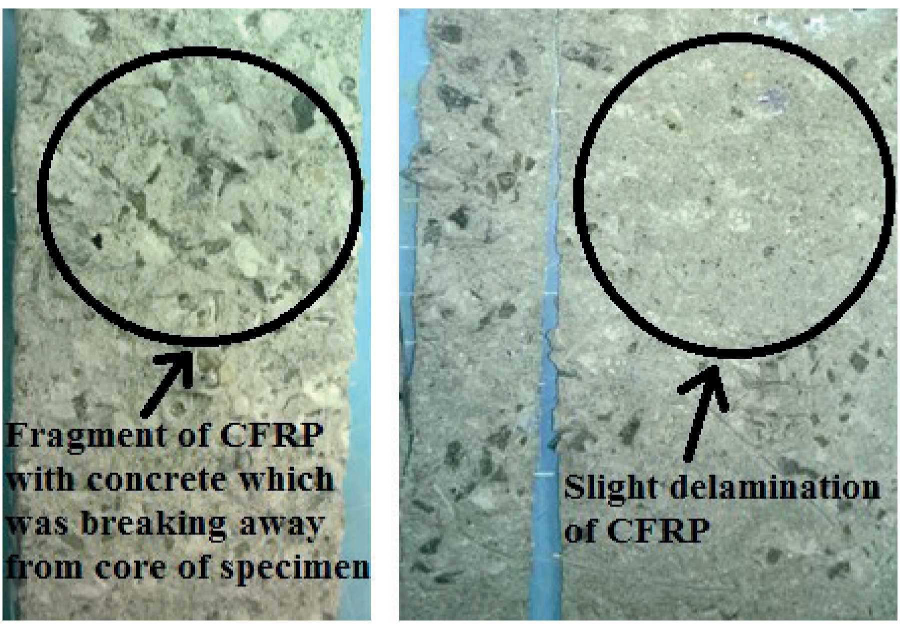

Fig. 6. CFRP sheets torn from NCC-CFRP (left) and HPCC-CFRP (right)

aggregates and cement paste were torn from the concrete core in the case of NCC-CFRP; however, in the case of HPC a small amount of aggregate and a surface layer of cement paste were detached from the surface of the HPCC-CFRP. This indicates a worse co-operation of the epoxy resin with the surface of high-performance concrete; however, it should be emphasised that this is a phenomenon reported in the literature [11, 14].

4. Conclusions

An experimental program was carried out to study the axial compression behaviour of normal concrete and high-performance concrete columns of circular cross-section confined externally with CFRP sheets. The main conclusions of the tests are noted below:

1. The stress–strain curves of the NCC-CFRP can be divided into two separate regions: firstly, the elastic stage involved with the transfer of stresses by the concrete; secondly, the strengthening stage, where stresses are transferred by CFRP confinement – this provides the columns with post-yield stiffness for load carrying;
2. The stress–strain curves of the HPCC-CFRP is close to being linearly elastic. After exceeding the load capacity, we observe a step loss of stiffness leading to the destruction of the element – this is not observed in the case of NCC-CFRP;
3. The failure of all CFRP columns occurred in a sudden and explosive manner and was preceded by typical creeping sounds;
4. The ultimate capacity of the confined concrete, given in terms of ultimate strength and axial strain, depends on the concrete core strength;
5. The confinement efficiency drops when the compressive strength of the concrete core increases. In the cases of NCC-CFRP and HPCC-CFRP, confinement caused a 130% and 33% increase in load capacity, respectively;
6. The adhesion of the epoxy resin to the concrete surface and its penetration depth depends on the type of the concrete with regard to strength. It is possible that the rupture of the jacket could be accompanied by a slight delamination of the layers.

The author would like to thank Mr Marek Kawalec, MSc. Eng., from SIKA Poland, for his donation of the strengthening materials and for the technical support provided.

This thesis was conducted within the framework of the regulation researches of AGH University of Science and Technology, Poland No 15.11.100.009.

References

[1] Berthet J.F., Ferrier E., Hamelin P., *Compressive behavior of concrete externally confined by composite jackets,* Part A: experimental study. Construction and Building Materials, 2005.

[2] Chikh N., Gahmous M., Benzaid R., *Structural Performance of High Strength Concrete Columns Confined with CFRP Sheets,* Proceedings of the World Congress on Engineering, 2012.

[3] Daiyu Wang, Zhenyu Wang, Scott T. Smith, Tao Yu, *Seismic performance of CFRP-confined circular high-strength concrete columns with high axial compression ratio,* Construction and Building Materials, 2017.

[4] EN 12390-13:2013 Testing hardened concrete, Part 13: Determination of secant modulus of elasticity in compression.

[5] Jiang S., Fernando D., Ho J.C.M., Heitzmann M., *Behavior of FRP confined ultrahigh-strength concrete columns under axial compression: An experimental study,* Mechanics of Structures and Materials: Advancements and Challenges, 2017.

[6] Jiang T., Teng J.G., *Analysis-oriented stress-strain models for FRP-confined concrete,* Engineering Structures, 2007.

[7] Lim J.C., Ozbakkaloglu T., *Confinement model for FRP-confined high-strength concrete,* Journal of Composites for Construction, 2013.

[8] Mayer P., Kaczmar J., *Właściwości i zastosowania włókien węglowych i szklanych,* Tworzywa Sztuczne i Chemia, 2008.

[9] Ostrowski K., Kinasz R., Cieślik J., Wałach D., Ahmida B., *Nośność elementów osiowo ściskanych na przykładzie kolumn z betonu i fibrobetonu wysokowartościowego wzmocnionych włóknami węglowymi,* Czasopismo Inżynierii Lądowej, Środowiska i Architektury, 2016.

[10] Ostrowski K., Kinasz R., Cieślik J., Wałach D., *The influence of CFRP sheets on strength of short columns produced from normal strength concrete and fibre reinforced concrete,* Technical Transaction, 2–B/2016.

[11] Sadowski Ł., Mathia T. G., *Multi-scale metrology of concrete surface morphology: fundamentals and specificity,* Construction and Building Materials, 2016.

[12] Sadowski Ł., Czarnecki S., Hoła J., *Evaluation of the height 3D roughness parameters of concrete substrate and the adhesion to epoxy resin,* International Journal of Adhesion and Adhesives, 2016.

[13] Sadrmomtazi A., Khabaznia M., Tahmouresi B., *Effect of Organic and Inorganic Matrix on the Behavior of FRP-Wrapped Concrete Cylinders,* Journal of Rehabilitation in Civil Engineering, 2016.

[14] Xiao Y., Wu H., *Compressive behavior of concrete confined by various types of FRP composite jackets,* Journal of Reinforced Plastic and Composites, 2003.

[15] www.sika.com (access: 07.04.2017).

[16] www.gorazdze.pl (access: 17.03.2017).