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COHESION TEST OF A SINGLE IMPREGNATED AR-GLASS ROVING IN HIGH-PERFORMANCE CONCRETE

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ABSTRACT

The development of light and very thin concrete building structures and demand for extremely thin elements in design are inter alia reasons for the development of composite materials as non-traditional reinforcement. Composite materials are currently used as reinforcement mostly in the form of fiber reinforced polymer bars similar to traditional steel reinforcement bars, but the last decade sees also rise in the use of technical textiles. This article is focused on the interaction between impregnated textile reinforcement and high-performance concrete matrix and its easy determination using originally modified pullout test. The second aim of this article is improvement of interaction conditions between reinforcement and cementitious matrix using fine-grained silica sand applied on the surface of the composite reinforcement similarly to the traditional fiber reinforced polymer reinforcement with commonly used diameters. To investigate an effect of this modification a bending test was performed on small thin concrete slabs with different amounts of reinforcement.

KEYWORDS

Concrete, High performance concrete, Textile reinforcement, Cohesion, Interaction, Roving, Alkali resistant glass, Surface treatment

INTRODUCTION

Textile reinforced concrete (TRC) is a new composite material made of high-performance concrete (HPC) reinforced with technical textiles. The properties of this material are still intensively researched and its use is steadily growing. The basic principle is identical to the traditional steel reinforced concrete. HPC has great mechanical properties regarding compression and textile reinforcement has similarly good parameters in tension. With proper utilization of the HPC properties it is possible to use lesser amount of concrete in comparison with traditional concrete for elements with similar load-bearing capacity which in turn leads to more environmentally effective elements [1]. The technical textiles used as reinforcement are chemically resistant and non-corrosive and these characteristics can be further improved by using epoxy resin or materials. The TRC elements therefore do not need as massive concrete cover of reinforcement as in the case of traditional reinforced concrete with steel reinforcement affected by corrosion. The most commonly used technical textiles as reinforcement are alkali-resistant glass, carbon, basalt and aramid.

This article is focused on the interaction of impregnated textile reinforcement in HPC matrix and its easy determination using originally modified pull-out test. In addition, this experiment was supplemented by the bending test performed on thin slabs to further verify and test the different amounts of reinforcement in cross-sectional area. This issue is relatively thoroughly dealt with in the case of fiber reinforced polymer (FRP) reinforcement with conventional diameters. Testing methods, interaction and methods for its improvement were already successfully proposed and measured. There are many articles and standards all around the world. Impregnated technical textiles using epoxy resin for homogenization are basically also FRP material with considerably smaller diameter, but standards for element design and the effect of interaction with the cement matrix have not been issued yet. There is also no standard with defined procedures to measure the interaction conditions.

Some articles about the interaction conditions of textile reinforcement were already published. This article is focused only on impregnated technical textiles. Portal [2] states that there is no standard methodology for measurement and evaluation of the TRC pull-out test. The pull-out test was set by the Krüger [3] and Lorenz and Ortlepp [4] asymmetric test. In their experiment samples of 400 x 100 x 15 mm were reinforced using one layer of technical textile. Various anchoring lengths were selected for the characterization of interaction conditions and also the moment of breaking point of textile reinforcement in the sample [5].

Banholzer [6] developed a one-sided test that is used for detection of broken light-fiber filaments. A sample is manufactured with dimensions of 10 x 10 mm and length of 30 mm using epoxy resin with a bundle of fibers in the middle of this prism. The fibers inside are therefore sufficiently protected against the steel jaws of the testing machine. The sample with epoxy prism is then embedded into the concrete matrix with dimensions of 50 x 50 mm and length of also 30 mm. During the testing procedure the sample of reinforcement is pulled out of the concrete part using a supported steel plate with displacement speed of 0.1 mm/min until the maximum displacement of 1.7 mm.

Very interesting testing methodology is also described in [5] with whole fabrics, not a single roving. This case also includes the effect of PP and PVA fibers that are used during the weaving of technical textile for yarn joining. These fibrils connect the whole fabric before the process of impregnation. The principle is analogous to the previously described testing methodology with a single roving. A portion of technical textile is inserted into the HPC specimen during the concreting with free length of fabric to be fixed into the testing machine. The fabric fixed into the testing machine is then pulled out from the concrete specimen using a steel frame as a support for the concrete part.

MATERIALS AND PREPARATION OF SPECIMENS

Concrete

The HPC mixture used in this experiment was developed at the Faculty of Civil Engineering, Czech Technical University in Prague (FCE CTU) for various applications [7]. This mixture was designed using mainly local sources of raw materials. It is a self-compacting fine-grained concrete and its composition is presented in Table 1. The HPC mixture used in this experiment was without any types of fibers. Water cement ratio was 0.25 and the water binder ratio was 0.20 for this mixture. Compressive strength tested on cubes with sides of 100 mm was equal to 140.5 MPa according to the standard CSN EN 12390-3. Tensile strength while bending tested on beams with dimensions of 160 x 40 x 40 mm was equal to 15.4 MPa according to standard CSN EN 12390-5. The same HPC recipe has been also used for several applications and research activities at the CTU like waffle and solid experimental facade elements [8] or in [9], [10]. Using the same concrete mixture allows the results to be compared with each other during the continuous process of alternative reinforcement development.

Tab. 1 - High-performance concrete mix composition

Component	**Unit**	**HPC**
Cement I 42.5R	[kg/m³]	680
Technical silica sand	[kg/m³]	960
Silica flour	[kg/m³]	325
Silica fume	[kg/m³]	175
Superplasticizers	[kg/m³]	29
Water (12°C)	[kg/m³]	171
Total	[kg/m³]	2340

Composite reinforcement

The technical textile reinforcement was produced from AR-glass fibers homogenized with epoxy resin. Rovings of AR-glass fibers were chosen from other types of technical textiles such as carbon, basalt or aramid due to the lower elasticity modulus, more visible interaction conditions and also due to economic aspects. Used rovings were from the company Cem-FIL® with a length weight (titer) of 2400 g/km (= 2400 tex), specific gravity of 2680 kg/m3, tensile strength of 1700 MPa and modulus of elasticity of 72 GPa according to the technical data sheet.

Epoxy resin SikaFloor-156 from the company Sika was used for the homogenization of the rovings. Basic parameters of pure resin are tensile strength in bending of 15 MPa and modulus of elasticity of 2.0 GPa. Specific gravity of the material is 1100 kg/m3 according to the technical data sheet. This resin has excellent penetrating properties due to its low viscosity and is therefore very suitable for roving homogenization. The epoxy resin accounted for about 65% of the cross-section of the impregnated roving due to the experimental manual nature of its production in the lab.

Part of the textile reinforcement was produced with a smooth surface formed by the epoxy resin, while the other part was created with surface modification utilizing fine-grained silica sand. This surface treatment ensures better interaction conditions between composite reinforcement and the cementitious matrix and was inspired in surface modification of the FRP bars with higher diameter. The application of this type of surface treatment in the case of textile reinforcement was described by Shi-ping [11] and the suitable size of silica sand grains was defined by previous author's research [12].

Specimen preparation

The specimens were prepared for two types of experimental verification of the composite reinforcement performance. The first experiment designed for determination of basic material interaction conditions was a pull-out test performed with a single impregnated roving with smooth surface in comparison with a roving with surface treatment using fine-grained silica sand. The second experiment was a four-point bending test performed as the most common way of loading for TRC applications. Molds for all TRC specimens were prepared individually using a system of laminated chipboards. One mold was made for five identical specimens for the pull-out test and the other one for three TRC panels for the four-point bending test.

The developed pull-out test method for single impregnated roving was originally inspired by American standard for testing of FRP reinforcements ACI 440.3R-03 “Guide test methods for fiber reinforced polymers (FRPs) for reinforcing or strengthening concrete structures” with modified specimen dimensions. The concrete part of specimens had constant dimensions of 100 x 100 mm with thickness related to the composite reinforcement diameter. First experiments were performed with the thickness close to the mentioned ACI standard with respect to the ratio to the other two dimensions, so the first thickness was 100 mm [13]. Especially in the case of single thin impregnated roving with the surface treatment the composite roving was usually broken before the start of slipping along the cementitious matrix. That leads to the thickness optimization using easy calculations. The resulting optimal thickness of the specimens for the used AR-glass roving 2400 tex with the diameter of approximately 2.0 mm was calculated to 20 mm.

The single roving homogenized by epoxy resin was fixed in the middle of the mold before the concreting of HPC part. A small cone made of silicone was installed on the composite roving inside the mold on the side where the composite reinforcement was fixed in the testing machine to prevent pulling of a shear cone from the HPC during the test procedure. This HPC shear cone would negatively affect results and cause skips on the measured curve. The anchoring length of each single impregnated roving was measured as the length of the roving inside a mold before concreting without the silicone cone. This length was also controlled after the pull-out test was performed by breaking of the HPC part and measuring the actual length. Mold was not treated with a demolding oil to prevent the contamination of the surface of the composite reinforcement.

The side of composite reinforcement fixed in testing machine was provided with epoxy sleeve enveloping it. Composite reinforcement has high tensile strength but is very fragile, so the epoxy sleeves were there to prevent damage of the impregnated rovings due to them being fixed in the testing machine. The epoxy sleeves replaced previously used steel ones [14], which made preparation of the specimens and manipulation with them much easier.

After initial preparations, the concreting was performed using self-consolidating HPC. The preparation of specimens is presented in Figure 1. Altogether 12 specimens were prepared - 6 specimens with the smooth surface and 6 specimens with the surface modification using fine-grained silica sand. The surface modification is visible in Figure 1.

Fig. 1 – Specimens preparation for the pull-out test.

Specimens for the four-point bending test were prepared in the form of small slabs with the dimensions of 100 x 360 x 18 mm. Reinforcement grids made of the impregnated AR-glass rovings were prepared in two different densities with 5 and 10 rovings per 100 mm specimen width and were cut to fit the intended specimen dimensions. The slabs were prepared in three variants. One with two 5 roving layers (2x5), second with two 10 roving layers (2x10) and third with four 10 roving layers (4x10). The last variant represents the maximum amount of textile reinforcement that allowed for proper concrete distribution throughout the specimens. All variants were prepared with a smooth surface and also with a surface modification, three specimens for each variant.

The casting process was performed layer by layer. That means a layer of HPC with a controlled thickness to ensure the proper concrete cover, then a TR was inserted, then a middle portion of HPC, another TR, and an upper layer of HPC in the case of specimens with two reinforcement grids and similarly in the case with four. The concrete cover layer was designed with a thickness of 4 mm and due to the chosen concreting process, no spacers were used. Specimens were not vibrated to prevent movement of the composite reinforcement to the HPC surface, the concrete HPC mixture was self-consolidating as mentioned above. The preparation of the specimens for the flexural test is presented in Figure 2.

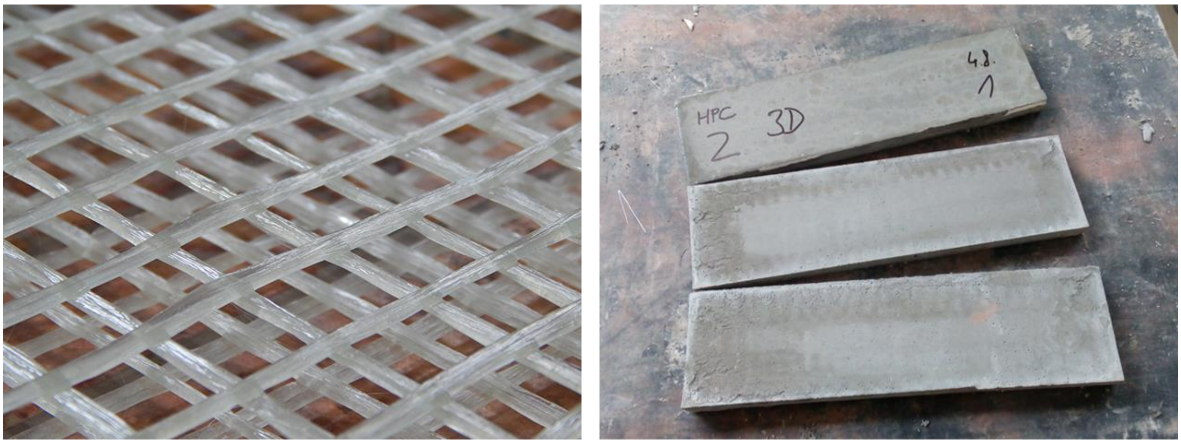

Fig. 2 – Specimens preparation for the four-point bending test.

All specimens were demolded one day after the casting process and were stored in constant conditions for another 27 days. The panels were stored in water tank and constant temperature of 22 °C. The specimens created for pull-out test were placed in air-conditioned environment with constant humidity of 60%. Dimensions and weight of the specimens were measured before testing.

EXPERIMENTS

Cohesion test

The developed pull-out method was focused on the complete curve of bond behaviour with a simple interpretation and application of results in the field of science as well as in the field of engineering and structures designing. As mentioned above this method was inspired by the ACI 440.3R-03 standard, but specimen dimensions were modified due to the small cross-sectional area of the composite reinforcement in comparison with traditional FRP reinforcement. Other aspects of the test set up were very similar to the traditional FRP cohesion test. Epoxy sleeves were installed only on one side of the rovings because of the safe and stable fixing to the testing machine without any damages to the roving filaments. Concrete part had constant dimensions of 100 x 100 mm and optimized thickness of 20 mm for single AR-glass impregnated roving with titer 2400 tex in this experiment. A view of the developed testing set up inspired by ACI standard is presented in Figure 3.

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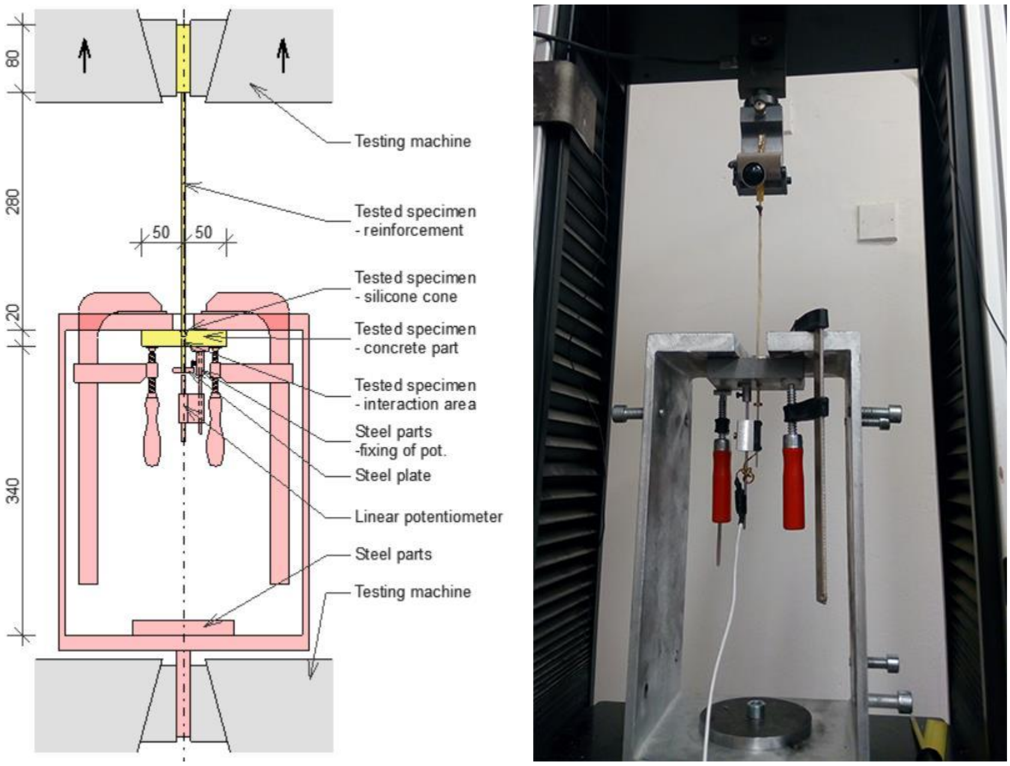

Fig. 3 – Basic scheme of own developed pull out test method inspired by ACI standard and picture of the actual setup.

Time, force, crosshead displacement and pull-out of the reinforcement were measured during the test procedure inspired by the ACI standard for a simple and direct determination of bond behaviour. Pull-out was measured on the free end of the impregnated roving by a potentiometer. The concrete part was equipped with a steel element made precisely by a lathe attached to the concrete by epoxy resin and the potentiometer was fixed in this steel part by a bolt. A circular rigid steel plate was similarly attached at the free end of the reinforcement which protruded from the concrete part by approximately 20 mm to provide stable contact area for the potentiometer. Considering the steel plate, the maximum theoretical pull-out value was around 15 mm. Detailed view of the potentiometer and its fixing on the HPC part is presented in Figure 4. The speed of loading was constant at 2.0 mm/min according to the prescribed tensile stress increment of approximately 2.0 MPa/s in ACI 440.3R-03 standard.

Fig. 4 – Detailed view of the bottom part of the concrete specimen with installed potentiometer and support constructions for the pull-out values measurement.

The results of the pull-out test are presented in Figure 5 and Figure 6 in the form of two graphs. Both graphs show pull out measured by the potentiometer on the X axis and corresponding force on the Y axis. Figure 5 shows overall comparison of specimens with smooth composite reinforcement and those with the surface treatment made of fine-grained silica sand. The test proved that there was little cohesion between HPC matrix and composite reinforcement with smooth surface as all rovings without surface treatment were pulled out of their HPC matrix. Figure 6 presents more detailed view focused on the specimens with impregnated rovings treated with fine-grained silica sand which showed almost perfect bonding with the HPC matrix. All impregnated rovings with surface treatment were broken before they could be pulled out. Another advantage of the surface treatment of the reinforcement is the stability of the results because no sample shows significant deviations as shown in Figure 6. Also, the maximum tensile strength of the impregnated rovings was without any negative caused by the embedded grains of silica sand. The presented curves of pull-out can be used for example for non-linear numerical modelling of crack development and crack opening of TRC elements using analytical methods or other numerical software.

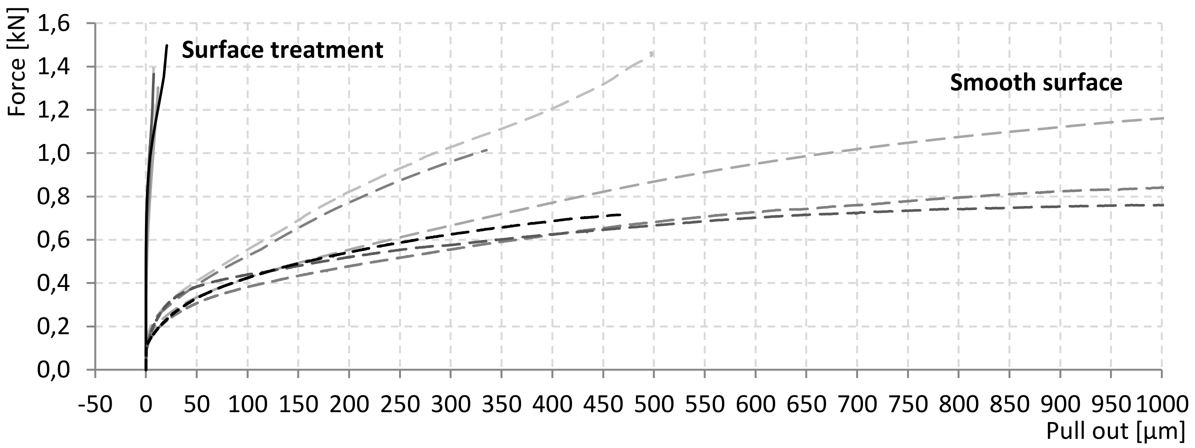

Fig. 5 – Results of pull-out test presented in the form of force – pull-out diagram using data from the testing machine and potentiometer showing rapid difference between the smooth surface and specimens with the surface modification.

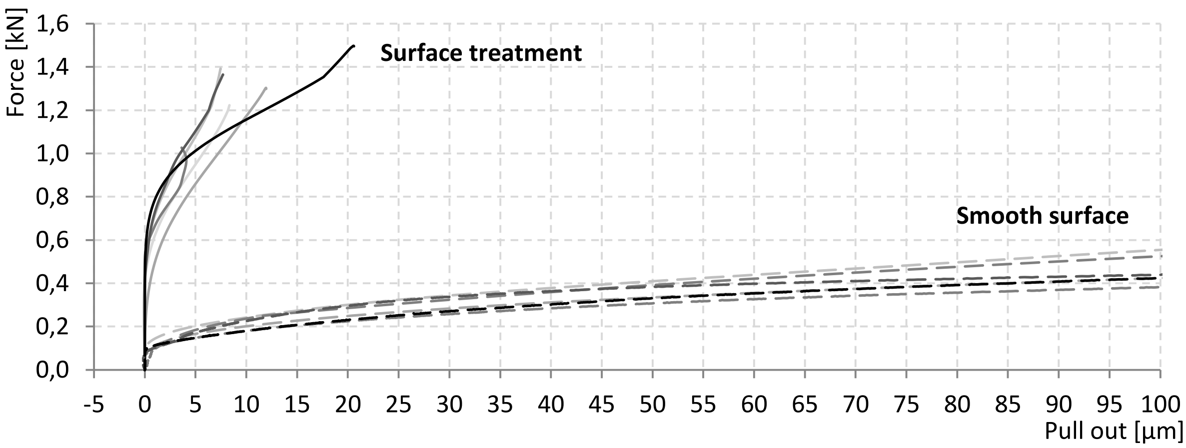

Fig. 6 – Results of pull-out test presented in the form of force – pull-out diagram using data from the testing machine and potentiometer. Detailed view on the beginning of the pull-out test with limited X axis showing rapid difference between the smooth and treated surface.

Four-point bending test

The four-point bending test was performed on small slabs with dimensions of 100 x 360 mm with constant thickness of 18 mm. Concrete cover of the composite reinforcement was designed to only 4 mm and was achieved by controlled application of HPC layers. The specimens were not vibrated to prevent the reinforcement movement to the HPC surface due to the lower density of the composite reinforcement compared to HPC. Three specimens were created for each group with the same designed amount of reinforcement. Six sets of samples were prepared in total.

Three variants with smooth surface and three with surface treatment using fine-grained silica sand were created. The first group contained two identical layers of composite reinforcement. One layer had 5 parallel impregnated rovings in the longitudinal direction with grid spacing of 22 mm. Grid spacing of rovings in transverse direction was 24 mm. The second group was also made with two identical layers of pre-prepared textile reinforcement but with 10 impregnated rovings in longitudinal direction spaced 10 mm from each other. The last third group of specimens was made with four layers of reinforcement with 10 impregnated rovings in longitudinal direction similar to the previous group. This combination of 4 layers with 10 rovings in each layer was the maximum possible amount of composite reinforcement for these specimen dimensions and composite reinforcement production technology, especially for the specimens with surface treatment. A view of the test setup and typical crack development is shown in Figure 7.

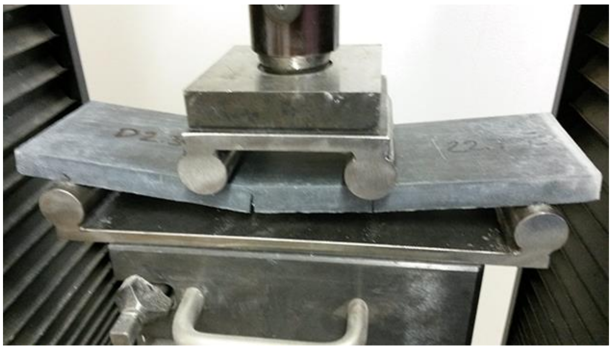
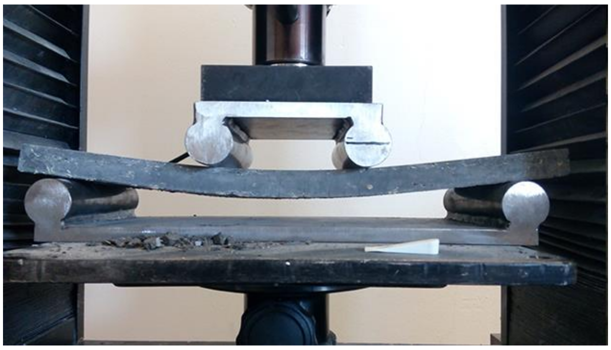

Fig. 7 – Typical crack development of 2x5 reinforcement with smooth surface on the left and 4x10 reinforcement treated with fine-grained silica sand on the right side.

Testing was performed with axial distance of supports of 300 mm and 100 mm in the case of loading supports. All supports had curvature with 15 mm radius. Monitored parameters during the testing procedure were magnitude of the reaction on the load cell and displacement of crosshead of the testing machine. Four-point bending test was performed on MTS 100 testing machine with controlled constant load increment of 2.0 mm per minute [12], [15], [16].

The results are presented in Figure 8, Figure 9 and Figure 10 in the form of force – displacement graph, because presentation of flexural stress on the y axis in not relevant after the initiation of the first crack in the HPC part despite the fact that it is commonly used. Always two graphs are presented side by side where the left side represents specimens with smooth composite reinforcement and the right side represents specimens with composite reinforcement with surface treatment.

Specimens with only two layers of textile reinforcement with five rovings in each layer are shown in Figure 8. The first sudden drop on the curve represents the formation of the first crack, creating a plastic joint, followed by an opening of the crack and an activation of the reinforcement. The load-bearing capacity of the specimen before the first crack initiation is given only by the tensile strength of the concrete without the contribution of the reinforcement. The small difference in this value between the samples with smooth reinforcement on the left and the samples with

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surface treated reinforcement on the right is due to a slight inconsistency in specimen thickness which varied from the intended 18 mm.

After the initiation of the first crack the specimens with smooth reinforcement typically formed one additional crack, each under one of the loading supports, after which the smooth reinforcement started slipping. Their behaviour under pressure was typical for a slightly reinforced concrete structures with wide cracks opening. The specimens with the surface treated reinforcement formed multiple more narrow cracks, due to significantly better interaction conditions between reinforcement and cementitious matrix. The pull-out was not that significant and much faster reinforcement activation lead to the multiple cracking, which is characteristic for structures with higher amount of reinforcement [12], [16].

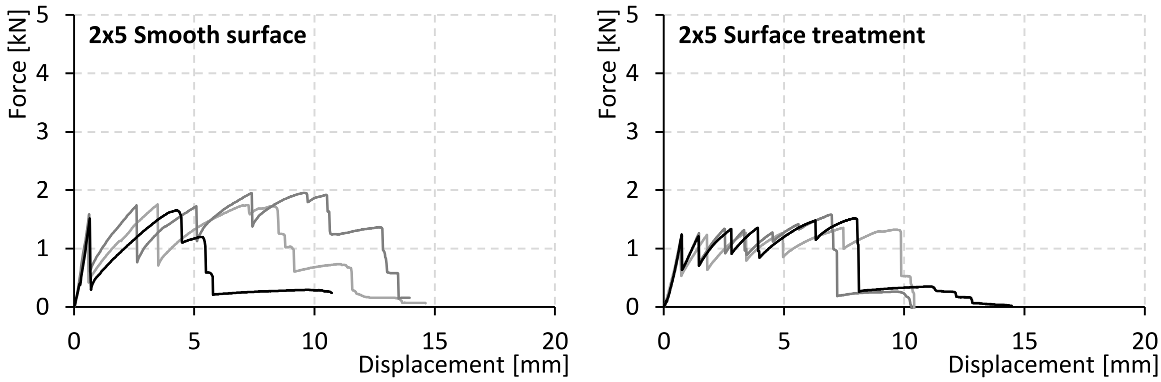

Fig. 8 – Force – displacement curves from the four-point bending test of specimens reinforced with 2x5 impregnated rovings with and without surface modification.

Very similar trend is presented in Figure 9 in the case of more heavily reinforced specimens with 10 rovings in each layer of reinforcement. Higher amount of reinforcement logically led to the higher maximum value of reached force in comparison to the specimens with 2x5 reinforcement. The specimens with smooth reinforcement on the left side show similar crack development as the specimens in Figure 8 on the right side with 2x5 reinforcement treated with fine-grained silica sand. The activation of surface treated 2x10 reinforcement is again much faster than in the case of its smooth counter-part. The specimens with surface modification also show higher ultimate reached force while also having lower displacement in the time of their collapse.

Figure 10 shows that the amount of reinforcement is so high in the cross-sectional area of the specimen that curves look more or less similar. The positive effect of the surface modification of composite textile reinforcement with fine-grained silica sand is much less significant in comparison with Figure 8 and Figure 9.

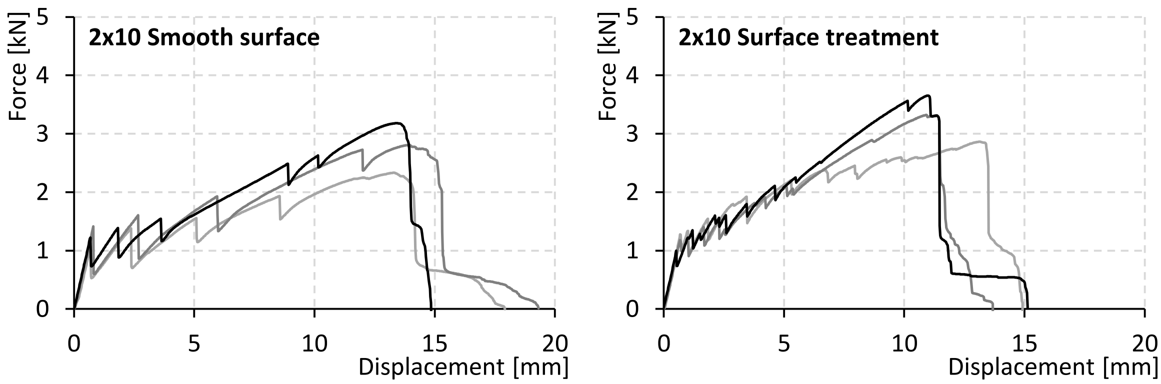

Fig. 9 – Force – displacement curves from the four-point bending test of specimens reinforced with 2x10 impregnated rovings with and without surface modification.

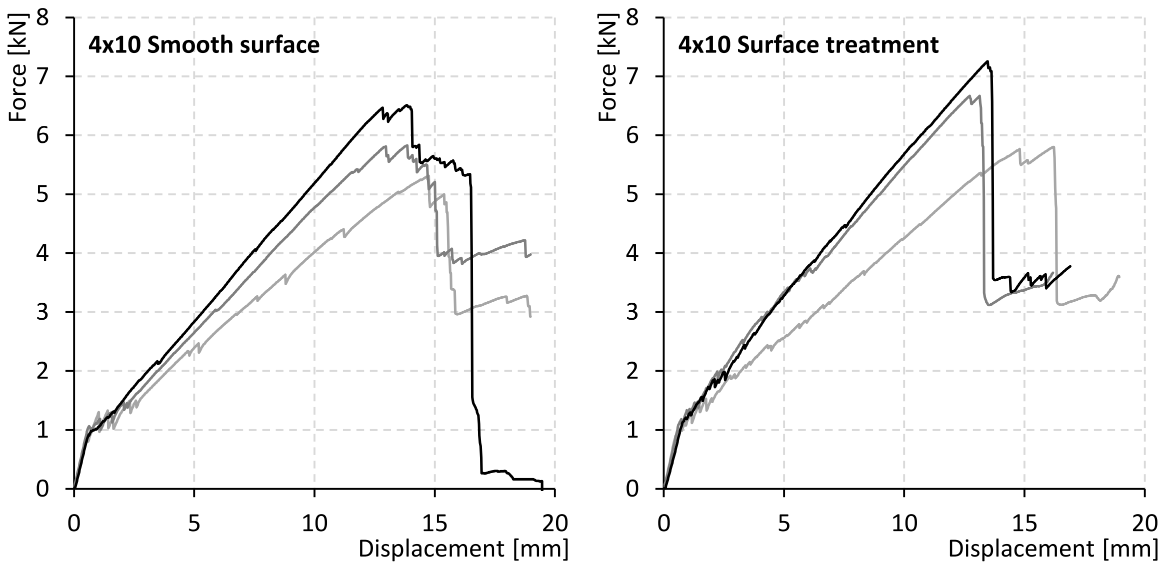

Fig. 10 – Force – displacement curves from the four-point bending test of specimens reinforced with 4x10 impregnated rovings with and without surface modification.

CONCLUSION

During the testing procedure of the own developed pull-out test method, the composite textile reinforcement in the form of a single impregnated roving with surface treatment made with fine-grained silica sand reached the maximum values of tensile stress in the composite reinforcement corresponding to the results of tensile test presented in a previous research. That means that the surface treatment using fine-grained silica sand has no significant negative effect on the tensile strength of the impregnated roving. The impregnated individual rovings were in most cases damaged (in the case of impregnated rovings with smooth surface after significant pull-out) where they were in contact with the surrounding HPC prism due to the fact that the reinforcement was pressed by the irregular contact area of the HPC during the process of reinforcement activation. The fibers near the surface of the textile reinforcement were therefore subjected to higher tensile stress, which leads to the weakening of the reinforcement and subsequent breaking of the roving in this area. Epoxy resin impregnation of the individual rovings however provides sufficient protection of AR-glass fibers in HPC matrix from premature damage for both smooth and modified reinforcement. The HPC part of tested specimens showed no signs of damage.

The difference between specimens with and without surface treatment is also clearly visible. The curves representing typical samples with smooth surfaces show a rapid pull-out of the reinforcement from the part of the HPC sample with higher pull-out values and lower corresponding force. After activation of the reinforcement in its full length, there is a very slow increase in force during the loading process due to poor interaction of both materials. This result signifies the need of large anchorage length of the smooth composite reinforcement required for the load transfer in the actual TRC element. The curves representing typical samples with surface modification provide much better results with higher contact stiffness. Grains of fine silica sand allow almost no slipping due to the high surface roughness.

The contact area of the reinforcement and cementitious matrix is constant in this method, due to the composite reinforcement passing completely trough the HPC prism. The pull-out is measured by a potentiometer placed on the free end of the reinforcement protruding from the HPC prism which ensures activation of the reinforcement in its whole length.

Textile reinforcement with surface treatment provides significantly better results regarding the crack formation and development as was also demonstrated by flexural bending test performed on small slabs using different variants and amounts of composite textile reinforcement. Better bonding conditions lead to a very short anchorage length for reinforcement activation without a significant loss of force due to the loading process controlled by constant increment of displacement. The ultimate bending strength was also a little higher. The most visible difference in the results is at the beginning of the curve during the process of reinforcement activation in the case of 2x10 impregnated rovings with smooth surface and with surface treatment. The surface treatment is therefore very effective and can also have economic benefits by saving reinforcement material.

It is also obvious from the presented figures that with a higher amount of textile reinforcement a bending behaviour similar to that of elements made of traditional materials and with traditional diameters of reinforcement can be achieved. This means that after the first initiation of cracks, there is no massive opening of cracks. This effect was achieved with a roving material made of alkali-resistant glass, which has a modulus of elasticity slightly higher than the HPC used. After impregnation with epoxy resin, the composite reinforcement as a whole even has a similar modulus of elasticity. It explains why such a large amount of composite reinforcement was needed to achieve those results during the bending test.

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