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ADVANCED SILICATE COMPOSITES – A CONTRIBUTION TO SUSTAINABLE CONSTRUCTION

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Abstract. In view of the increasing number of natural and man-made disasters and the increasing economic and social problems, it is necessary to adapt the existing principles and methods of structural design, the corresponding construction techniques, and the operation of buildings to make them more sustainable, resilient, and adaptable to new situations in changing natural and socio-economic conditions in the world. Recent research and development of concrete composition, production technology, and development of concrete constructions, intensified over the last 20 years, have led to the improvement of technical parameters while reducing environmental impacts. Due to the optimization of the mixture, new types of concrete have significantly better characteristics from the perspective of strength, mechanical resistance, durability, and resistance to extreme loads.

The paper presents examples and results of research focused on the use of new types of silicate composites and their effective combinations in the case study. It is generally necessary to apply new silicate composites in such a way that their potential is used to the maximum. The aim is to present the possibility of new practical and effective application of modern materials with an emphasis on reducing environmental impacts and at the same time increasing the resilience of structures. It covers the utilization of high-performance concrete as a protective and load-bearing thin skin with textile reinforcement using carbon textiles tube in combination with recycled concrete aggregate core.

Developed technical solutions could contribute to addressing the Sustainable Development Goals (SDGs), which the United Nations set out in 2015 as a 2030 action plan.

Keywords: Concrete, sustainability, textile reinforcements, textile reinforced concrete skin, recycled aggregate concrete, high-performance concrete, RAC core, HPC skin.

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1. Introduction

Concrete is gradually becoming a building material with a high potential for technical solutions meeting these new requirements, leading to a necessary reduction of environmental impacts and the consequent necessary improvement of properties in the conditions of a changing climate. Considering the amount of produced concrete, the optimization of concrete structures represents a great potential for improving the complex quality of structures from the perspective of sustainable development. One of the ways can be a completely new look at concrete structures and the search for the optimal application of new silicate materials, or their combinations. It can be sandwich constructions, combinations of concrete, or combinations of reinforcements. The paper just presents example and partial results of research focused on the use of new types of silicate composites and their effective combinations in the case study. It is generally necessary to apply new silicate composites in such a way that their potential is used to the maximum. It covers also use of high-performance concrete (HPC), for example, as a protective and load bearing thin skin permanent formwork with textile reinforcement using wound carbon textiles in combination with recycled concrete aggregates (RAC) core. RAC was chosen for this experiment at the beginning because of a higher difference in mechanical parameters and durability compared to HPC and also due to a better environmental profile.

HPC performs well in terms of durability and is highly suitable as a protection for other materials that struggle in this regard. Today there is an effort to use HPC more; nevertheless, it is expensive and, from the point of view of environmental impact, this is not an optimal way. The use of these HPC mixtures in combination with a weaker one can be a very attractive solution. It can reduce its consumption and helps to extend the usage of RAC. Many researchers is describing how to improve RAC within the changes in the mixture, but there are also experiments with combining these materials to improve the durability and reduce HPC consumption, for example [1]. There was an experimental study based on the axial behaviour of circle-shaped columns consisting of UHPC cover layer (shell) with carbon FRP grid and usual cast-in-place concrete with steel reinforcement inside, which is a fairly similar principle as in this thesis. Similar research describes, for example, beams on the same principle [2]. The author also describes here the progress of the UHPC layer thickness, which is really reduced, and the core again consists of usual concrete and steel reinforcement again [3].

2. MATERIALS USED FOR THE EXPERIMENT

2.1. CONCRETE

As mentioned above, both concrete mixtures used in this experiment were developed at the CTU. In the case of HPC it was Department of Architectural Engineering, Faculty of Civil Engineering. The HPC mixture used in this experiment was developed and optimized in last years at the CTU in Prague for different applications. The HPC composition recipe is presented in Table 1. It is a self-compacting fine-grained concrete without any fibers. Materials used for the experiment are primarily from local sources, and components are: CEM I 42.5 R cement, silica sand with two particle sizes and maximum grain sizes 1.2 mm, silica flour with one particle size, silica fume and one type of PCE superplasticizer. The mixture reduces the amount of water in water/cement ratio to only 0.25 and therefore significantly improves the mechanical properties. The direct tensile strength of the used HPC is experimentally determined to be 5.0 MPa according to the ČSN 73 1318 standard. The tensile strength in bending is 16.8 MPa on prisms 40 × 40 × 160 mm with a distance between supports of 100 mm according to the ČSN EN 12390-5 standard. Compressive strength is 106 MPa on 100 mm cubes according to ČSN EN 12390-3 standard. The static modulus of elasticity is 49.2 GPa on prisms 100 × 100 × 400 mm according to ČSN ISO 6784 standard [4, 5].

Mix content	**$\mathrm{kg\,m^{-3}}$**
Cement I 42.5R	650
Technical quartz sand D 0.1/1.2 mm	1 200
Technical quartz powder ST 6	235
Silica fume (microsilica)	85
Superplasticizer based on PCE	26
Water (at 12 °C)	175
Total	2 368

TABLE 1. HPC mixture design.

In the case of RAC it was developed at the Laboratory of Composite Structures, University Centre for Energy Efficient Buildings. A mixture with 100 % replacement of natural aggregate with recycled brick was chosen. Therefore, this is a lower quality concrete, especially in terms of modulus of elasticity and durability. Physical, mechanical, deformation, and thermal properties were tested according to valid Czech standards. The detailed composition of the matrix is described below in the Table 2. Samples of dimensions 100 × 100 × 400 mm, 150 × 150 × 150 mm, and 100 × 100 × 100 mm were used for the testing. The average compressive strength of the RAC mixture measured on cubes with 100 mm sides after 28 days of hardening was 24.4 MPa [6].

Mix content	**$\mathrm{kg\,m^{-3}}$**
Cement I 42.5R	274
Recycled aggregate 0/4	773
Recycled aggregate 4/8	18
Recycled aggregate 8/16	845
Water (at 12 °C)	290
Total	2 200

TABLE 2. RAC mixture design.

2.2. REINFORCEMENT

The textile reinforcement was produced manually by winding from carbon fiber homogenized with epoxy resin. The rovings from the company Tenax® STS40 F13 24K (Teijin, Tokyo, Japan) were used with a length weight (titer) of 1 600 g km^{-1} (= 1 600 tex), a tensile strength of 4 400 MPa, and a modulus of elasticity of 240 GPa, according to the technical data sheet. Epoxy resin SikaFloor-150® from the company (Sika, Brno, Czech Republic) was used for homogenization of the rovings. The basic parameters of pure resin are a tensile strength in bending of 15 MPa and a modulus of elasticity of 2.0 GPa. Fine-grained silica sand with grain sizes from 0.1 mm to 0.6 mm was used for surface modification to increase cohesion with the concrete matrix [7].

FRP basalt reinforcement positioned in each corner was used to support the cross-wound textile reinforcement, as the textile reinforcement was wounded over it. The used diameters of FRP bars were 2.2 mm and 6.0 mm. It is a commercial product. Young's modulus of basalt FRP reinforcement is 37 GPa and tensile strength is 980 MPa according to the technical data sheet. Traditional steel reinforcement was used as a reinforcement of RAC. Young's modulus of the steel reinforcement is 200 GPa and the tensile strength is 500 MPa according to the technical data sheet.

3. SPECIMEN PREPARATION AND DESIGN

3.1. VARIANTS OF SELECTED SPECIMENS

All HPC shells specimens were made at first as 1.20 m long elements (prisms) and subsequently cut to the required dimensions. The whole research study contained 4 types of the HPC shell – plain concrete without any reinforcement or fiber reinforcement, concrete including PP fibers MasterFiber 012 (amount 1 kg m^{-3}), concrete including PVA fibers MasterFiber 401 (15 kg m^{-3}), and concrete with laboratory

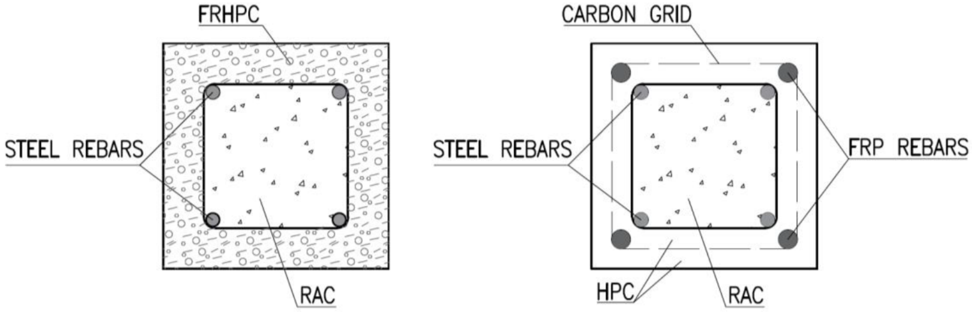

Figure 1. Cross-section scheme of basic variants without and with the cros-wound textile reinforcement [3]. Both diagrams represent the variant with the 18 mm HPC shell, variant with the 8 mm HPC shell thickness was also prepared.

prepared cross-wound carbon textile reinforcement. Every mentioned type was also prepared in two variants of thickness – 8 mm and 18 mm. The cross-sectional area of all samples for the case study was $100 \times 100\,\text{mm}^2$. For the comparison specimens with RAC core (mentioned above) were also prepared [3]. A diagram of the 18 mm HPC shell filled with RAC is presented in Figure 1.

Two lengths of specimens were evaluated through the three-point bending test in this case study, specimens with a length of 400 mm focusing on shear capacity and with length 600 mm length focusing on flexural capacity. Another set with a length of 400 mm was prepared for the compressive strength test. Additionally, 200 mm long samples were prepared for testing with phenolphthalein to determine the depth of carbonation and to evaluate the influence of the thin HPC shell. For each set, 3 specimens were prepared and filled with recycled-aggregate concrete [3]. This article presents only a part of the whole research – a three-point bending test of the 400 mm specimens, showing the significant contribution of the wound carbon textile reinforcement to shear force transfer.

3.2. Specimen preparation

A steel hollow pipe was used as the base of the formwork, to form the HPC shell hollow core and for basic manipulation during the whole process. It was covered with the 2 mm thin separation layer. For samples consisting of plain HPC skin or fiber-reinforced HPC skin, steel pipe could be placed into wooden formwork and get ready for casting. Samples including carbon textile reinforcement had then added square-shaped hoops to a steel pipe, which enabled the attachment of four FRP rebars, one in each corner of the hoop and situated to keep the textile grid in the middle of the HPC skin layer. The carbon roving grid was cross-wound around the FRP rebars consisting of 24 rovings for each sample – 12 rovings in each direction at an angle of 45°. In the next step, the textile reinforcement was homogenized using epoxy resin and sand-coated with fine-grain quartz sand for perfect cohesion with HPC [8]. The hardening of the epoxy resin took about 7 days in total. A detailed view of the cross-wound reinforcement is presented in Figure 2 on the left. The columns were casted using HPC and closed until the next day when the formwork was removed, the view on the mold is presented in on the right. The prepared columns were stored in the room with constant humidity and after hardening were cut into the length 400 mm or 600 mm for the bending test. Hollow samples were completed with this step and view on the HPC skin during the process of hardening is presented in Figure 3 on the bottom.

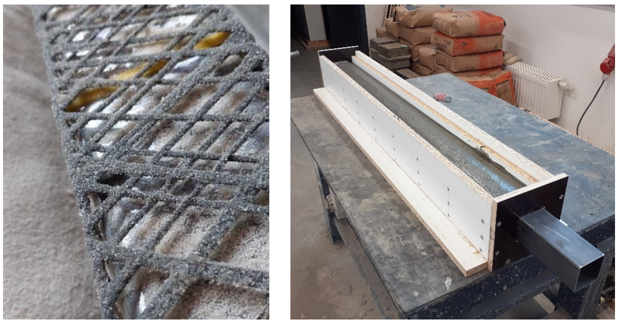

Figure 2. Cross-wounded carbon textile reinforcement after impregnation using epoxy resin and covered with fine sand (on the left) and one specimen after the process of HPC casting, visible steel supported core (on the right).

The samples with RAC cores were reinforced using conventional steel rebars with 6 mm in diameter. Rebars were placed into the inside corners. Traditional steel reinforcement was impossible to add due to the small laboratory dimensions. The positive is that the shear forces were transformed only through the knit from the carbon textile reinforcement. The specimens were filled with recycled-aggregate concrete as the core [3]. View on the filled specimens is presented in Figure 3 on the bottom.

3.3. Three-point bending test setup

The three-point bending test was performed according to the EN 12390-5 technical standard (Flexural strength of test specimens). Scheme for testing and

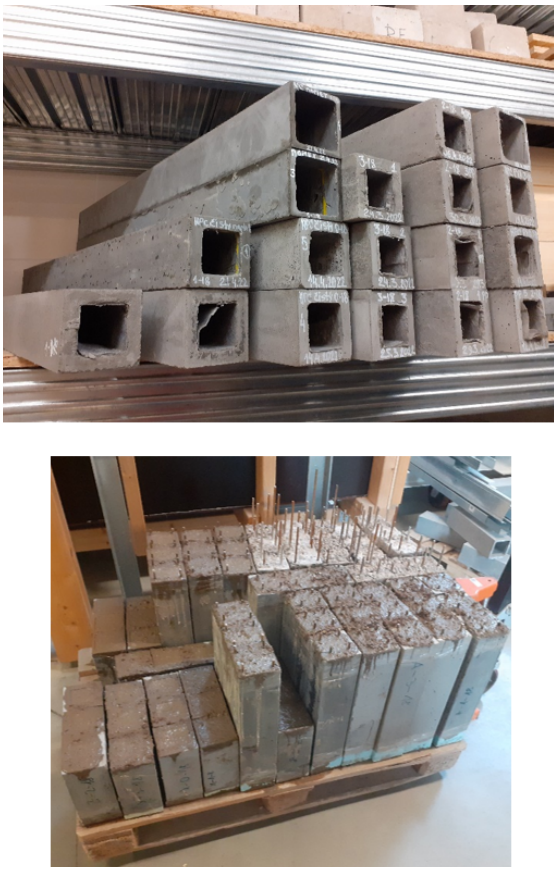

FIGURE 3. Hollow HPC skin during the process of hardening before cutting (on the top) and specimens already cut and filled with RAC after the process of concreting with visible steel reinforcement in the corner (on the bottom).

real setup is visible in the next chapter about the results. For hollow or filled specimens with dimensions 100 × 100 × 400 mm, the support pin distance was 300 mm and the upper one was exactly in the middle of this distance.

4. RESULTS AND DISCUSSION

All presented bending tests were carried out until the complete collapse of the sample. One of three specimens was chosen for comparison from each set. The representative curve from each group is presented in Figure 4 for the hollow specimens. Plain HPC, PP, and PVA fibers have a very similar trend. However, during the test, the crack development was different, especially in the case of PVA fibers. Plain HPC and HPC with PP fibers logically had only one crack during the loading process and subsequently collapsed. However, the PVA fibers allowed the proper development of a higher number of cracks – multiple cracking. The specimen with carbon textile was very different. There was a massive multiple-cracking process, proper activation of the load-bearing textile reinforcement and significantly greater load-bearing capacity.

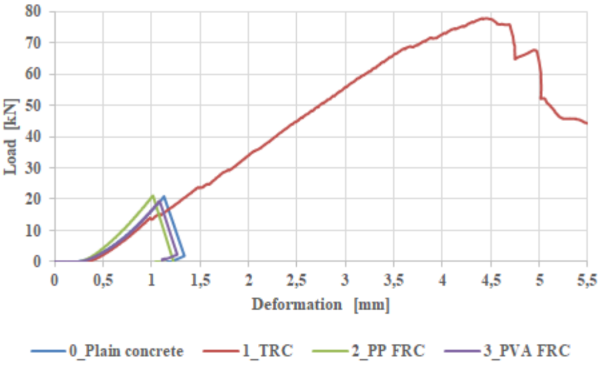

FIGURE 4. Hollow permanent HPC skin (formwork) with the thickness 18 mm for representative samples. Visible massive positive influence of carbon composite reinforcement in HPC.

The testing procedure was the same also for specimens filled by RAC and wit additive longitudinal steel reinforcement. The trend for all samples was similar. It was clear that the response was significantly improved due to the added steel reinforcement, and the specimen was able to carry more force than when the first crack was initiated for plain HPC skin and skin with fiber reinforcement. It is presented in Figure 5.

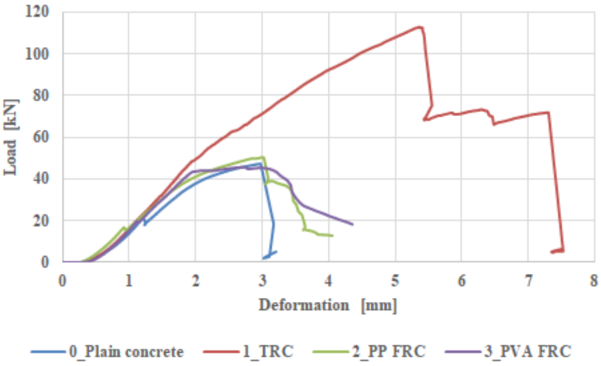

FIGURE 5. Permanent HPC formwork (shell) filled by RAC and additional traditional longitudinal steel reinforcement with the thickness of the HPC shell of 18 mm for representative samples. A massive positive influence of the wound carbon reinforcement in HPC.

The option with carbon knit is again significantly the best set of all, although it needs some changes to provide, show, and take the advantage of the filled core. And that is a great result of the study. The core did not have a chance to interact completely due to the over-reinforced shell with carbon knit. Concrete crushing was also included in the construction joint and there was also delamination of the reinforcement. The view of the specimens of HPC filled with RAC after the testing procedure is presented in Figure 6. Both again with thickness of reinforced HPC skin 18 mm. Plain HPC (on the top) has one visible crack between the upper and bottom support, and HPC skin with a carbon textile knit (on the bottom) has different types of failure – delamination due to the short anchorage length of the reinforcement.

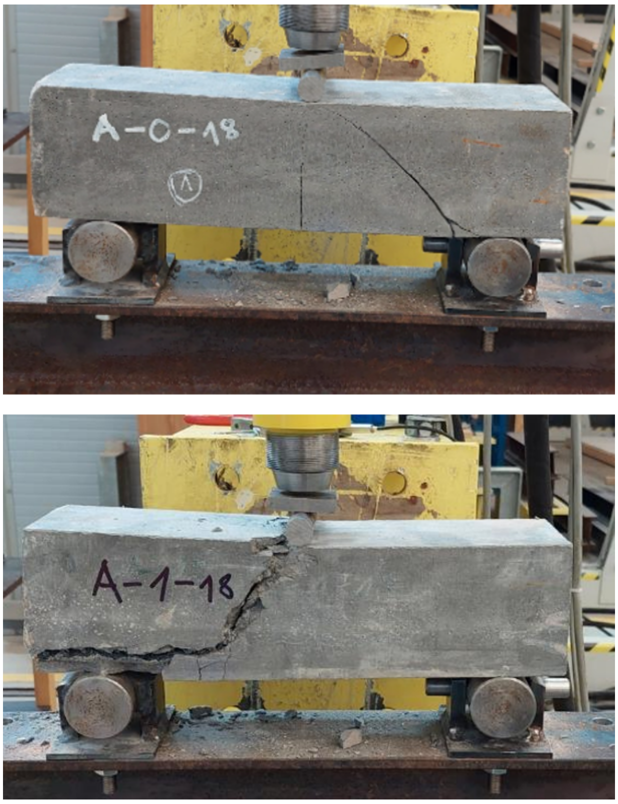

Figure 6. Examples of HPC specimens filled with RAC after the testing procedure. Both with a shell thickness of 18 mm. Plain HPC shell (on the top) and with the cross-wound carbon textile reinforcement (on the bottom) [3].

5. Conclusions

For this case study of the possibility of applying modern silicate composites with new approaches aimed at reducing the carbon footprint of concrete structures in general, a combination of HPC and RAC with 100 % replacement of natural aggregates with recycled brick aggregates was chosen, as well as a combination of impregnated textile reinforcement and traditional steel reinforcement. The samples were also supplemented with fiber reinforcement for the possibility of comparison. For the presented variants, four materials of HPC were used with the skin thickness of 18 mm – plain concrete, polypropylene fiber-reinforced concrete, polyvinyl alcohol fiber-reinforced concrete and textile-reinforced concrete.

Plain HPC skin has bad results during the mechanical test, and also PP fibers in HPC skin have really no impact in the way of strength and should be used, e.g. eliminating shrinkage. PVA fibers in the HPC skin showed the most visible progress due to core filling with RAC. Textile-reinforced sets had incredible results, although there was an over-reinforcement problem which pushed back possible progress thanks to RAC filling. The load-bearing capacity was huge despite the fact that the filled RAC core had no chance to interact and support the process. Thanks to this case study of the new approach to concrete construction, there is space for some adjustments and optimalisation in future research, for sure.

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