

A STUDY OF THE BEHAVIOR OF SAMPLES OF HIGH-PERFORMANCE CONCRETE SHELLS WITH FILLED CORE EXPOSED TO COMPRESSION

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ABSTRACT. The production of concrete has a huge impact on the environment, especially due to its emission of CO₂. Nowadays, it is required to reduce CO₂ emissions and at the same time reduce the consumption of non-renewable resources. One way to achieve these goals is through the usage of recycled aggregate. However, when these materials are used, there are significant changes in the properties of concrete, particularly a reduction of mechanical strength, modulus of elasticity, and durability. This article presents the possibility of using a thin shell made of high-performance concrete as core protection of a concrete sample with recycled aggregate to improve the abovementioned properties. Moreover, using high-performance concrete as the outer layer enables the potential of high-performance concrete to be exploited. The article describes the influence of different shell reinforcements on the failure of the samples under compressive stress. A shell layer without additional reinforcement was used for the reference samples. Other sets of samples contained dispersed reinforcement in the form of polypropylene or polyvinyl alcohol fibers. The last reinforcement was a technical textile – a laboratory-prepared composite grid made of carbon rovings. All samples were subjected to a compressive test and the failure mode of the samples was observed in particular.

KEYWORDS: Fiber-reinforced concrete, textile-reinforced concrete, high-performance concrete, concrete with recycled aggregate, fiber reinforcement, textile reinforcement, carbon footprint.

1. INTRODUCTION

Carbon footprint, specifically CO₂ production is a profoundly discussed issue, and the construction industry is not an exception nowadays. Hence concrete with recycled aggregate is progressively more desired product and it tends to be more investigated than years ago as its usage is one of the methods how to effectively affect this area. Nevertheless, RAC (in abbr. recycled-aggregate concrete) is disadvantaged by its properties usually deteriorated apart from conventional concrete mixtures, primarily its durability [1]. Therefore other improvements are taken into account such as, among other things, outer protection by the HPC (in abbr. high-performance concrete). On the other hand, HPC itself is environmentally inauspicious and there is an effort to lower its consumption in general. Due to these facts, HPC used as the only protection layer is incorporating and decreasing its problems also when textile reinforcement is used [2–10]. The experiment described in this article deals with the combination of these two mentioned materials with the view of improved properties unlike using each material separately. Samples were made as squared thin shells (protective layer) of HPC and subsequently filled with RAC mixture, hollow shells were also made as reference samples. The examination was made as a gradual

loading in compressive strength and all variants used were compared.

2. MATERIALS

Both of the concrete mixtures used in this experiment was evolved at the Department of Architectural Engineering, Faculty of Civil Engineering CTU in Prague. The average compressive strength of the HPC mixture measured on cubes of the length of the edge 100 mm after 28 days of hardening was 120 MPa. The average compressive strength of the RAC mixture measured on cubes of 100 mm in length of the edge after 28 days of hardening was 24.4 MPa. The detailed composition of the matrix is described below in Tables 1 and 2.

Mix content	kg m ⁻³
Cement I 42.5R	650
Technical quartz sand $D_{max} = 1.2$ mm	1 200
Technical quartz powder ST 6	235
Silica fume (microsilica)	75
Superplasticizer based on PCE	18
Water (at 12 °C)	190
Total	2 368

TABLE 1. HPC mix design.

Mix content	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 mix design.

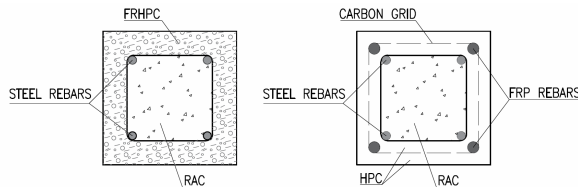


FIGURE 1. Fiber-reinforced 18 mm thick shell filled with RAC (on the left), HPC including carbon grid 18 mm shell filled with RAC (on the right).

Shell preparation included a few following steps. A squared steel section with a separative layer was settled with plastic hoops made by a 3D printer. Those hoops were used as a base for longitudinal reinforcement around which the carbon grid was knitted. Concrete embedment was made in a horizontal position, samples were first made as 1200 mm long. After concrete hardening, the steel section was pulled out. Subsequently, every element was cut into three 400 mm long specimens.

For the outer layer made of HPC, three types of reinforcement were used namely carbon textile reinforcement grid, dispersed polyvinyl alcohol fibers, and dispersed polypropylene fibers. Within the samples including the carbon textile reinforcement grid, fiber-reinforcement rebars (in abbr. FRP) were also used as a base for carbon roving knitting for the requested shape of the grid. Carbon grid was subsequently carbonated with epoxy resin to hold the shape and the damp surface was covered with fine sand for better cohesion with the concrete mixture. To all the filled samples with RAC were also added conventional steel rebars to the inner corners. Cross section area of the whole sample was 100 × 100 mm and the length was approximately 400 mm. Outer layers were made in two thicknesses – 8 mm and 18 mm. An exemplary scheme is presented in Figure 1 and summary of all the specimens is described and counted in Table 3.

2.1. EXPERIMENT

A compression test of the specimens was performed at the UCCEB laboratory according to the EN 12390-3 standard (Compressive strength of test specimens) [11], and hydraulic press Controls MMC-Multitest was used. All samples were gradually loaded until the collapse.

3. RESULTS OF THE COMPRESSION TEST

The first group of samples tested was hollow shells with 8 mm thickness. Plain concrete shells, as expected, were fractured completely due to the fragility of the material as there is no reinforcement. Polypropylene fibers had a negative impact toward mechanical properties as they are smooth and thin and caused only the weakening of the shell structure accordingly to the lower compressive strength in comparison with plain concrete shell. The form of fracture was exactly the same as by plain concrete – completely fractured through as much as the concrete without reinforcement. Polyvinyl alcohol fiber-reinforced hollow samples reported visible transition apart from previous groups. These sturdy fibers tend to keep the whole element undivided as its integrity is improved although it was already destructed. Moreover, compressive strength is not weakened such as by PP fibers whereas is comparable with the plain concrete shell results. Furthermore, were textile-reinforced samples tested. Above all, compressive strength was significantly increased because of carbon grid reinforcement usage for these elements. The reinforcement grid was not destroyed, conversely, its strength caused concrete spalling around and near the reinforcement carbon grid. A representative sample for every group of reinforcement is shown in Figure 2.

When testing a group of hollow specimens with a thickness 18 mm of the shell, a form of fracture was equal to the thinner hollow samples. Proportions between average compressive strengths were a bit different by dispersed fiber-reinforced elements apparently according to different ratios of fiber length and thickness of the shell layer.

The next step was testing 8 mm shells filled with recycled aggregate concrete. The samples including only a plain concrete shell were fractured completely around the core. The outer layer was spalled because of the fragility of the material and also no cohesion or interaction between RAC and HPC layers through the construction joint. PP fiber-reinforced specimens reported the same behavior as plain concrete. Nevertheless, average compressive strength was a bit improved apart from the first set. PVA fibers seemed to be the optimal solution for this outer layer in terms of greater integrity which kept the whole element undivided although many big cracks were visible. The average compressive strength was quite lowered but this was probably caused due to low permeability of the RAC mixture which did not reach all space inside so hollow weak spots remained and destruction of the HPC layer was easier because of no interaction with the core. Textile-reinforced specimens reported significantly improved behavior apart from all the previous sets. Samples were probably over-reinforced because the carbon grid was not broken (as by hollow samples), so except for concrete spalling through the cover layer around the grid, specimens reported greater integrity and also increased average compressive strength.

Formwork	Plain concrete	MasterFiber 012	MasterFiber 401	Carbon grid
8 mm	3 pcs hollow	3 pcs hollow	3 pcs hollow	3 pcs hollow
	3 pcs with RAC	3 pcs with RAC	3 pcs with RAC	3 pcs with RAC
18 mm	3 pcs hollow	3 pcs hollow	3 pcs hollow	3 pcs hollow
	3 pcs with RAC	3 pcs with RAC	3 pcs with RAC	3 pcs with RAC

TABLE 3. Summary of the tested samples.

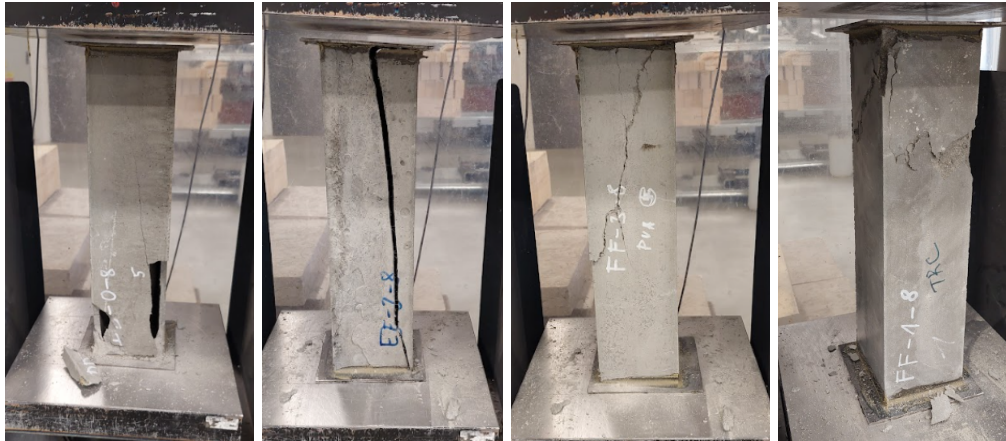


FIGURE 2. 8 mm hollow shells by materials from left: plain concrete, PP FRC, PVA FRC, TRC (carbon grid).



FIGURE 3. 8 mm shells filled with RAC by materials from left: plain concrete, PP FRC, PVA FRC, TRC (carbon grid).

sive strength. A representative sample for every group of reinforcement is shown in Figure 3.

Throughout the 18 mm shells filled with RAC, forms of fracture were quite similar to the thinner ones. Within testing these thicker elements had an important role the construction joint as a weakest part of the element. Spalling in this area was frequently visible that is to say cohesion or interaction between RAC and HPC layer is near zero.

4. CONCLUSION

In this experiment were tested two types of specimens – hollow shells made of HPC in two thicknesses 8 mm and 18 mm and four variants of (non)reinforcement and subsequently these shells filled with recycled ag-

gregate concrete.

Firstly, hollow sets of specimens will be described. Plain concrete shells without reinforcement were always, as was expected, super fragile due to high-performance concrete mixture properties and there were no differences between plain concrete sample variants. Polypropylene fibers reported also fragile fracture at all and they also influenced the mechanical properties of the samples. From Figure 4 is noticeable that the impact of adding these fibers on compressive strength is a bit unpredictable. Some variants were worse than plain concrete although this was not a standard according to other sets. This is probably caused by fiber dosage, orientation, or equal dispersion but these fibers themselves have no effect on compressive

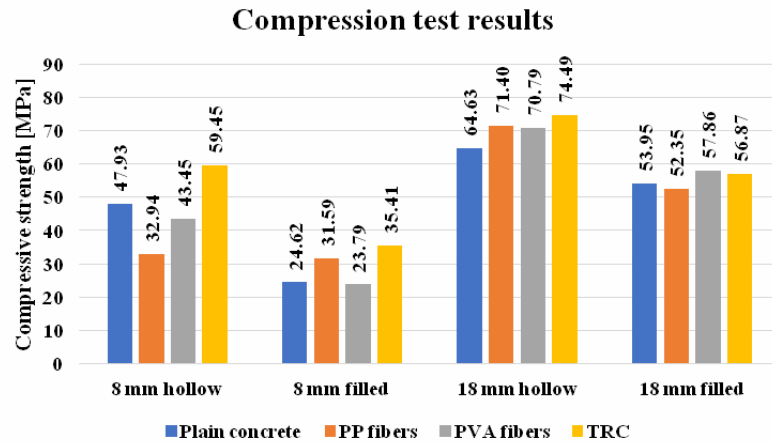


FIGURE 4. Compression test results in MPa.

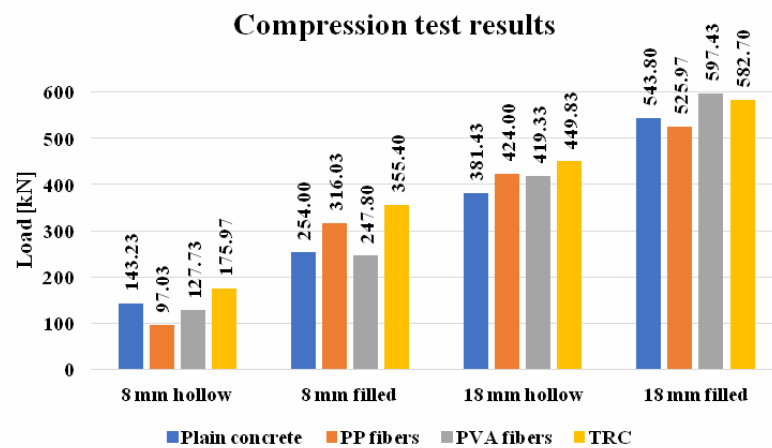


FIGURE 5. Compression test results according to maximal load.

strength and they can easily weaken the cross-section area during the loading process. Polyvinyl alcohol fibers confirmed the same principle described by PP fiber reinforcement. Nevertheless, PVA fibers ensure greater integrity thus safer construction fracture. TRC samples reported the highest compressive strength values and also the most favorable form of fracture.

The remaining sets filled with recycled aggregate concrete reported similar properties when it comes to shell and its materials. Nevertheless, it is important to pay heed to construction joint as the weakest area of the sample. Nearly all filled samples, with no need to distinguish thicknesses, were broken mostly through the construction joint because of a lack of cohesion or interaction between the inner core and outer layer, which should be improved a lot. All of the average compressive strengths for every type is in Figure 4.

Because of different cross-section area due to filling with RAC, results taken as maximal load before collapse are in Figure 5 for better comparison between hollow shells and their filled alternatives. In general, significant improvement was caused for each set by just filling with RAC and subsequent interaction. When it comes to a complete summary, the best results at all

were achieved within PVA fibers and textile carbon grid reinforcement.

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REFERENCES

- [1] C. Lima, A. Caggiano, C. Faella, et al. Physical properties and mechanical behaviour of concrete made with recycled aggregates and fly ash. *Construction and building materials* **47**:547–559, 2013. <https://doi.org/10.1016/j.conbuildmat.2013.04.051>
- [2] P. C. Aitcin. *High-performance concrete*. CRC Press, 1998.
- [3] P. C. Aitcin. The durability characteristics of high-performance concrete: a review. *Cement and concrete composites* **25**(4-5):409–420, 2003. [https://doi.org/10.1016/S0958-9465\(02\)00081-1](https://doi.org/10.1016/S0958-9465(02)00081-1)
- [4] P. S. Song, S. Hwang. Mechanical properties of high-strength steel fiber-reinforced concrete. *Construction*

- and building materials* **18**(9):669–673, 2004. <https://doi.org/10.1016/j.conbuildmat.2004.04.027>
- [5] T. Bittner. *Experimentální ověřování prvků z textilního betonu*. Ph.D. thesis, VUT, 2019.
- [6] H. Tian, Z. Zhou, Y. Zhang, Y. Wei. Axial behavior of reinforced concrete column with ultra-high performance concrete stay-in-place formwork. *Engineering Structures* **210**:110403, 2020. <https://doi.org/10.1016/j.engstruct.2020.110403>
- [7] E. Kafková. *Influence of different fibre reinforcement on the failure of textile reinforced concrete*. Bachelor thesis, VUT, 2021.
- [8] R. F. Zollo. Fiber-reinforced concrete: an overview after 30 years of development. *Cement and concrete composites* **19**(2):107–122, 1997. [https://doi.org/10.1016/S0958-9465\(96\)00046-7](https://doi.org/10.1016/S0958-9465(96)00046-7)
- [9] W. Brameshuber. Textile reinforced concrete-state-of-the-art report of RILEM TC 201-TRC, RILEM, 2006.
- [10] M. Etxeberria, A. R. Marí, E. Vasquez. Recycled aggregate concrete as a structural material, RILEM, 2006.
- [11] European Committee for Standardization. EN 12390-3; Testing hardened concrete – Part 3: Compressive strength of test specimens, 2019.