Acta Polytechnica CTU Proceedings **33**:357–362, 2022
https://doi.org/10.14311/APP.2022.33.0357

HIGH-PERFORMANCE CONCRETE CONTAINING WASTE VITRIFIED TILES

Diana Mariaková[a, b, *], Kristina Fořtová[a], Zuzana Jirkalová[a, b], Tereza Pavlů[a, b], Petr Hájek[a, b]

[a] *University Centre for Energy Efficient Buildings of Czech Technical University in Prague, Třinecká 1024, 273 43 Buštěhrad, Czech Republic*

[b] *Department of Architectural Engineering, Faculty of Civil Engineering, Czech Technical University in Prague, Thákurova 7, 166 29 Prague 6, Czech Republic*

[*] corresponding author: diana.mariakova@cvut.cz

Abstract.

This contribution deals with the possibility to use waste vitrified tiles (VT) in high-performance concrete. Silica powder normally used in high-performance concrete is replaced by waste vitrified tiles in 25, 50, 75 and 100 %. The basic experiments are tested, such as water absorption, flexural strength and compressive strength. The durability is examined, freeze-thaw resistance is tested in 25, 50, 75 and 100 freeze cycles. The results are evaluated and compared with the reference high-performance concrete, containing silica powder. The recipe of concrete is optimized based on these results.

Keywords: Durability, high-performance concrete, waste vitrified tiles.

1. Introduction

The production of construction and demolition waste (CDW) raised almost up to 42 % in 2019 in Czech Republic. From 2017, the numbers are similarly high, ranging around 40 % [1]. However, in recent years there appears increasing tendency of recycling and reusing CDW. There are studies dealing with the possibilities of the CDW utilization and management of processing it [2–4].

Building materials create almost a half of worldwide produced materials. Due to the rapid industrial development the problems are appearing all over the world such as decreasing sources of non-renewable resources and environmental impact connected with the extraction, manufacturing and transporting these materials. At the same time, it is necessary not to omit the associated processes, which release exhaust gases such as carbon dioxide, or processes associated with the end of life of these raw materials and materials produced from them [5]. The problem of the necessity of landfilling these used materials is connected as well.

Sustainable development and the entire global problem with environmental impacts is related with the volume of produced concrete and the buildings made from this material [6]. Replacing of primary raw materials needed to create concrete mixtures is convenient because of saving the primary sources and the energy resources required to obtain these raw materials. Concrete is the most used produced material in the world. The high production is the reason of the studies searching for alternative components such as natural aggregates substitutes or cement replacement.

There are studies dealing with the possibility to replace natural aggregate in concrete, due to the decreasing applicable sources of this material. The standards require the fulfillment of strict criteria for the selection of suitable aggregates for use in concrete, especially for road aggregates. The studies are examined the utilization of bricks, glass or used concrete as recycled aggregate in concrete [7–11]. The main problem is the possibility of an undesired alkali-silica reaction which needs to be discussed and evaluated [12].

The possibility of replacing (fully or partially) cement or cementitious materials are examined as well. Researches are testing the appropriate amount of replacement or the convenient grain size[13–15]. Verification of the selected material properties is essential for proper interaction of the components in concrete mixture. Basic chemical composition, pozzolanic properties or toxicity [16] should be observed to valorize pertinency of future use.

This paper deals with the use of waste vitrified tiles in concrete as a partial of full replacement or silica powder (cement replacement). Vitrified tiles were selected as a waste to recycle with pozzolanic properties. The aim of this research is to verify basic properties and find the suitable amount of the replacement to preserve the special properties of high-performance concrete, such as low water absorption or high durability of the material.

This paper describes behavior of concrete mixtures containing waste vitrified tiles compared with the reference high-performance concrete in the view of durability and mechanical properties, such as flexural and compressive strength. The testing methods are described and explained, the results are measured, calculated and evaluated. Based on the results, the recipe of concrete mixture is optimized and adapted for future use in construction industry.

2. Materials and Methods

The mixtures were designed based on the original HPC recipe developed in Department of Architectural Engineering [17]. Silica powder was replaced by powder from waste vitrified tiles which is a ceramic material composed of feldspar and clay, almost without any pores. The material is produced under high pressure (350 – 450 kg / cm) and fired at temperatures above 1200 degrees Celsius. The replaced part of silica powder was 25 %, 50 %, 75 % and 100 % by weight. Original HPC recipe was used as the reference sample, needed during the evaluation and data comparison in the next chapters.

2.1. Materials

Materials according the basic recipe were chosen from local sources and suppliers for preparation 5 types of high-performance concrete mixtures. These materials are: Portland cement CEM I 42.5 R (CEM), natural aggregate in two fractions (NA - fine and coarse aggregate), silica powder (SP), microsilica, superplasticizers and water. Silica powder was replaced by the waste vitrified tiles (VT) in the mixtures, the replacement is described in Table 1. Amount of cement, natural aggregate, microsilica and water remains same in the mixtures, the variable segment is the amount of used waste vitrified tiles as a silica powder replacement. More detailed information about the properties of used materials are not crucial for the experiments and the results of this work.

Based on the properties of vitrified tiles, there was an assumption of positive impact on the results. The pozzolanic properties of used waste material can have a positive effect on the resulting strength of concrete samples. This work aims to find the ideal percentage part to replace the silica powder.

2.2. Methods

Basic experiments were made to analyse properties of high-performance concrete containing waste vitrified tiles. Due to the vitrified tiles characterization water absorption, compressive strength and flexural strength were examined. The durability was verified as well in 25, 50, 75 and 100 freeze cycles.

2.2.1. Water absorption

Another measured parameter was the absorption of the samples. Water absorption of concrete samples is a necessary parameter measured in construction due to its use in structures exposed to external influences, such as water. After 28-days concrete hardening, the samples were weighed, stored in water, then reweighed and the water absorption rate was evaluated based on the measured parameters.

2.2.2. Compressive strength

There were two types of tested samples. First type was cube 150 × 150 × 150 mm. The tested surface Ac was 150 × 150 mm. Second type was the fragments with the tested surface A_c 40 × 40 mm. Fragments from the samples after flexural strength testing were used.

In this contribution, the destructive method of compressive strength test was used. The procedure was followed the Czech standards ČSN EN 12350-1, ČSN EN 12390-1, ČSN EN 12390-2, ČSN EN 12504-1 and ČSN EN 12390-4 [18–22]. The samples were tested under the speed 2400 N/s, peak 20 kN and the test is completed when the sample breaks, after that the maximum measured force is recorded. Five samples from each mixture were tested and the average value was then calculated from the results. Whole method is described in ČSN EN 12390-3 [23].

2.2.3. Flexural strength

The tested samples were specimens with dimension 40 × 40 × 160 mm according to ČSN EN 12390-5 [24]. The flexural strength is defined in ČSN EN 1015-11 [25] by three-point press. The samples were tested under the speed 50 N/s, peak 2 kN and the test is completed when the sample breaks. Three samples from each mixture were tested and the average value is calculated from the highest measured force. This work is dealing with three-point bending, it is possible to use another method - four-point bending.

2.2.4. Freeze-thaw resistance

The tested samples were 40 × 40 × 160 mm. This test was made according to ČSN 73 1322 [25]. The samples were cooling by water for four hours to -20 °C and then warming up for two hours to 20 °C. Preparation before freeze thaw resistance test includes data recording. The samples were tested in 25, 50, 75 and 100 cycles, three specimens from each concrete mixture. The compressive strength and the flexural strength are measured after freeze-thaw cycles and effect of the cycles (25, 50, 75, 100) is examined and evaluated.

3. Results

3.1. Water absorption

The water absorption was tested on the cube samples 50×50×50 mm on three specimens from each concrete mixture. The results of water absorption test are shown in the table below (Table 2). Due to similar character of the concrete mixtures it was expected the similar value of water absorption. All the mixtures values are ranging around 3 %, more detailed results are in Table 2.

3.2. Compressive strength

Compressive strength was tested on two types of samples. First type was cube specimen 150 × 150 × 150

Component (g)	CEM	NA	SP	MS	H2O	VT
REF	650	1200	240	175	180	0
VT25	650	1200	180	175	180	60
VT50	650	1200	120	175	180	120
VT75	650	1200	60	175	180	180
VT100	650	1200	0	175	180	240

Table 1. Recipe of the tested HPC mixtures.

Mixture	Weight of wet sample (g)	Weight of dry sample (g)	Water absorption
REF	294.9	285.9	3.124%
VT 25	300.4	292.7	2.642%
VT 50	293.8	285.7	2.823%
VT 75	292.8	283.7	3.220%
VT 100	294.7	285.5	3.199%

Table 2. Water absorption of tested high-performance concrete samples.

Mixture	Strength after 28 days (MPa)	σ	Percentage relation to REF
REF	119.32	4.75	100.00%
VT 25	121.64	3.51	101.94%
VT 50	112.89	3.47	94.61%
VT 75	122.42	3.72	102.60%
VT 100	116.34	6.19	97.50%

Table 3. Compressive strength (cubes 150 × 150 × 150 mm).

Mixture	Strength after 28 days (MPa)	σ	Percentage relation to REF
REF	128.50	4.64	100.00%
VT 25	122.96	5.42	95.70%
VT 50	125.49	4.54	97.66%
VT 75	131.29	3.66	102.17%
VT 100	129.39	2.35	100.70%

Table 4. Compressive strength (fragments of blocks 40 × 40 × 160 mm).

Mixture	Strength after 28 days (MPa)	σ	Percentage relation to REF
REF	12.31	0.59	100.00%
VT 25	11.05	0.13	89.76%
VT 50	12.60	0.28	102.24%
VT 75	12.14	0.76	98.64%
VT 100	12.54	0.34	101.84%

Table 5. Flexural strength (blocks 40 × 40 × 160 mm).

mm, the tested surface was 150 × 150 mm. The results are shown in Table 3. The values are raging 112.89 – 122.42 MPa, highest results were achieved by the mixture containing 75 % and 25 % of vitrified tiles. The reference samples HPC showed slightly lower values, the percentage relation to the REF samples is also shown in the table below (Table 3). The lowest values have the concrete mixture containing 50% of waste vitrified tiles. However, the value is still high up to 94.61 % compared to the REF HPC sample.

The second tested type of sample were fragments of blocks 40×40×160 mm. The used specimens were tested on the flexural strength before, the tested surface was 40 × 40 mm. Summarized results are in Table 4. The results were ranging 122.96 – 131.29 MPa and were similar as the results from the cube compressive strength testing. The best results were measured on mixture VT 75 in both cases (on cubes 102.6 % compared to the reference sample, on block fragments 102.17 % compared to the reference sample.

3.3. Flexural strength

Flexural strength was tested on specimens 40 × 40 × 160 mm. The blocks were made in sets of three samples from each concrete mixture. The average values were calculated based on the maximum measured force and are shown in Table 5.

The highest values were measured on the mixtures containing 50 % and 100 % of waste vitrified tiles substitution. In the comparison with the reference samples, the lowest value has the mixture VT 25 which is observed in the most measured parameters (compressive strength on the fragments of blocks and water absorption).

3.4. Freeze-thaw resistance

The samples were tested in the sets of three samples. Each sample was tested in the flexural strength and compressive strength. Samples were exposed to 25, 50, 75 and 100 freeze-thaw cycles to confirm the ability of high-performance concrete to resist freeze-thaw cycles. The results validate that there is no negative effect to this quality caused by the addition of new material - waste vitrified tiles - and all the values are summarized in Figure 1 and Figure 2 below.

The flexural strength results of reference sample (REF) showed increasing tendency depending on the increasing number of cycles. The values went from 11.54 MPa (strength after 28 days) up to 17.64 MPa (strength after 100 cycles). This tendency was observed on the samples from mixture VT100 and VT25. The increasing tendencies did not occur on samples VT50 and VT75. However, the samples did not show any cracks or signs of failure and after all the minimal measured strength is still 82 % (VT50) compared to the REF. On the other hand, the average values measured on mixture VT100 achieved 102 % compared to the REF.

The compressive strength was measured on the fragments of samples 40 × 40 × 160 mm. The tested surface was 40 × 40 mm. In the compressive strength experiment, mixture VT75 showed the best results, where the strength achieved 105 % compared to REF. On the other hand, the lowest result was measured on VT100, where the strength stayed on 93% compared to REF. Nevertheless, the result is satisfying in the relation with the other average values raging 95 – 98 % after 100 freeze-thaw cycles. The compressive strength after 25 cycles is ranging from 98 – 104 % compared to the REF, 92.5 – 105 % after 50 cycles and 91 – 98 % after 75 cycles. It is possible to say, that the results met the expectations.

4. Conclusion

Four mixtures containing different amount (25 %, 50 %, 75 % and 100 %) of waste vitrified tiles as a substitutional material were designed and tested (mixtures VT25, VT50, VT75 and VT100). All the results were compared with the reference sample REF (high-performance concrete made from primary raw materials). The water absorption was experimentally tested, the absorption of mixtures with tiles was similar to the REF. The absorbency values of all tested samples were around 3 %. The flexural strength was tested and VT50 and VT100 showed the highest results. The measured force and calculated strength were higher than the values of the REF. Similar numbers were evaluated on the samples after compressive strength experiment. However, the highest results were provided by VT25 and VT75 (cubes) and VT50 and VT100 (fragments of blocks). All these results were higher than results of REF.

The freeze-thaw resistance was verified. The freezing cycles don't have the impact to the results. The compressive strength of the samples made from the mixtures containing 25, 50, 75 and 100 % substitution of silica powder by waste vitrified tiles was raging 91 – 105 % compared to the reference sample. The flexural strength achieved 116 % compared to the reference sample after 50 freeze-thaw cycles, rest of the samples were ranging from 82 % up to mentioned 116 %. When omitted maximal and minimal, the average value was 99 % compared to the REF.

Based on the experiments and the results, it is possible to say that the proposed mixtures are suitable for further testing and verification of their properties, which so far confirm the possibility of their use as HPC. The similarity of the resulting properties of the tested mixtures containing waste tiles with the reference mixture is given mainly by the composition of used waste vitrified tiles.

Therefore, the resulting values correspond to the assumptions made at the beginning of this experiment and forms a solid basis for further research.

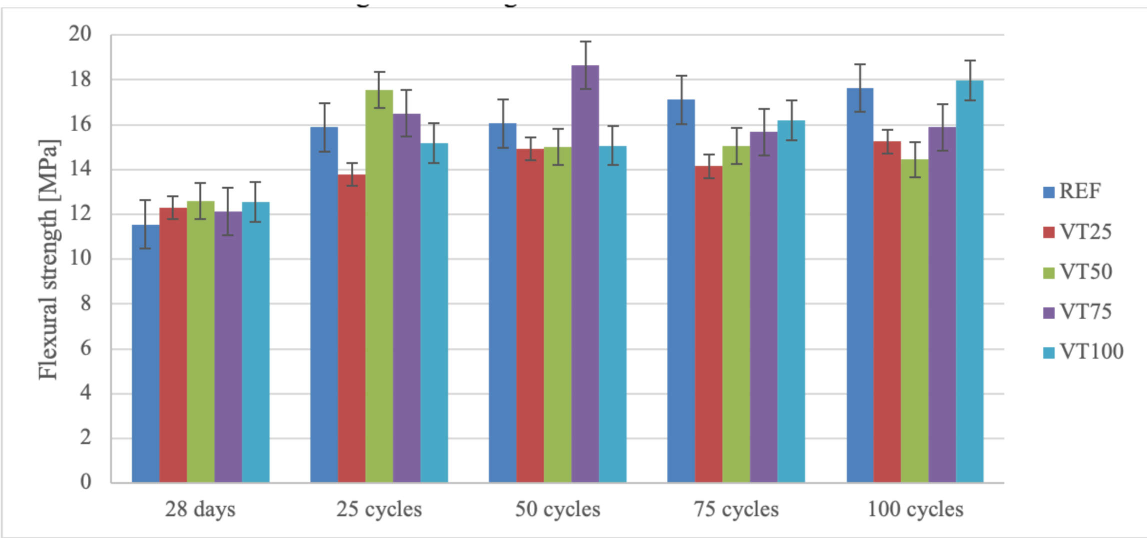

Figure 1. Flexural strength values after freeze-thaw resistance experiment.

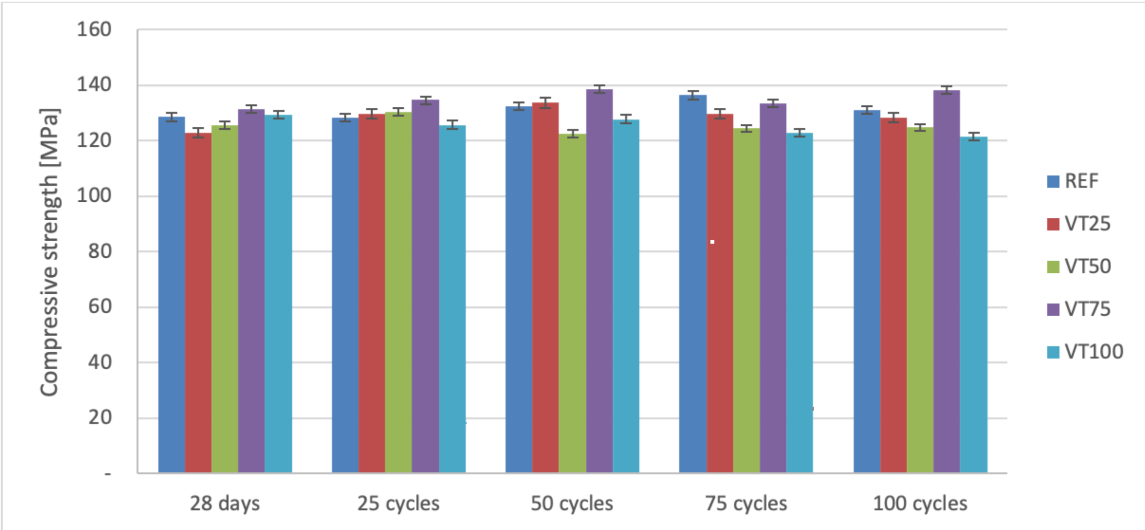

Figure 2. Compressive strength values after freeze-thaw resistance experiment.

Acknowledgements

This research was funded by Ministry of Education, Youth and Sports LTAIN19205 Design of performance based concrete using sand reclaimed from construction & demolition wastes. This work has been supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS19/093/OHK1/2T/1 - Use of waste materials in HPC in design applications and SGS21/096/OHK1/2T/11 - Influence of chemical properties on the use of waste materials in concrete applications.

References

[1] Český statistický úřad, 2021. `https://www.czso.cz/csu/czso/cesko-v-roce-2019-vyprodukovalo-37-mil-tun-odpadu`.

[2] C. Rodríguez, I. Miñano, M. Aguilar, et al. Properties of Concrete Paving Blocks and Hollow Tiles with Recycled Aggregate from Construction and Demolition Wastes. *Materials* **10**(12), 2017. `https://doi.org/10.3390/ma10121374`.

[3] S. Dadsetan, H. Siad, M. Lachemi, et al. Construction and demolition waste in geopolymer concrete technology: a review. *Magazine of Concrete Research* **71**(23):1232-52, 2019. `https://doi.org/10.1680/jmacr.18.00307`.

[4] M. I. Sánchez De Rojas, F. P. Marín, M. Frías, et al. Properties and Performances of Concrete Tiles Containing Waste Fired Clay Materials. *Journal of the American Ceramic Society* **90**(11):3559-65, 2007. `https://doi.org/10.1111/j.1551-2916.2007.01944.x`.

[5] Kamala R, Krishna Rao B. Reuse of Solid Waste from Building Demolition for the Replacement of Natural Aggregates. International Journal of Engineering and Advanced Technology (IJEAT), 74-76., 2012.

[6] P. Hájek, C. Fiala, M. Kynčlová. Life cycle assessments of concrete structures - a step towards environmental savings. *Structural Concrete* **12**(1):13-22, 2011. `https://doi.org/10.1002/suco.201000026`.

[7] O. M. Olofinnade, J. M. Ndambuki, A. N. Ede, et al. Effect of Substitution of Crushed Waste Glass as

Partial Replacement for Natural Fine and Coarse Aggregate in Concrete. *Materials Science Forum* **866**:58-62, 2016. https://doi.org/10.4028/www.scientific.net/MSF.866.58.

[8] P. B. Cachim. Mechanical properties of brick aggregate concrete. *Construction and Building Materials* **23**(3):1292-7, 2009. https://doi.org/10.1016/j.conbuildmat.2008.07.023.

[9] A. Tareq Noaman, G. Subhi Jameel, S. K. Ahmed. Producing of workable structural lightweight concrete by partial replacement of aggregate with yellow and/or red crushed clay brick (CCB) aggregate. *Journal of King Saud University - Engineering Sciences* **33**(4):240-7, 2021. https://doi.org/10.1016/j.jksues.2020.04.013.

[10] D. Acosta Álvarez, A. Alonso Aenlle, A. J. Tenza-Abril, et al. Influence of Partial Coarse Fraction Substitution of Natural Aggregate by Recycled Concrete Aggregate in Hot Asphalt Mixtures. *Sustainability* **12**(1), 2019. https://doi.org/10.3390/su12010250.

[11] Mariaková D, Jirkalová Z, Fořtová K, et al. Rizika alkalicko-křemičité reakce v recyklovaném betonu. In: 17. konference Speciální Betony - Betony v extrémních podmínkách a ostatní speciální betony (ID: 344331). Lísek, Bystřice nad Pernštejnem, česká republika: Ostrava - Zábřeh, Česká republika, 2020.

[12] F. A. Khan, K. Shahzada, Q. Sami Ullah, et al. Development of Environment-Friendly Concrete through Partial Addition of Waste Glass Powder (WGP) as Cement Replacement. *Civil Engineering Journal* **6**(12):2332-43, 2020. https://doi.org/10.28991/cej-2020-03091620.

[13] A. Pathak. Effect of Silica Fume and Fly Ash as Partial Replacement of Cement on Strength of Concrete. *SSRN Electronic Journal*, 2020. https://doi.org/10.2139/ssrn.3577292.

[14] C. Rahul Rollakanti, C. Venkata Siva Rama Prasad, K. K. Poloju, et al. An experimental investigation on mechanical properties of concrete by partial replacement of cement with wood ash and fine sea shell powder. *Materials Today: Proceedings* **43**:1325-30, 2021. https://doi.org/10.1016/j.matpr.2020.09.164.

[15] Mariaková D, Anna Mocová K, Fořtová K, et al. Ecotoxicity and Essential Properties of Fine-Recycled Aggregate. *Materials* **14**(2), 2021. https://doi.org/10.3390/ma14020463.

[16] M. Novotná. High Performance Silicate Composites in Environmentally Optimized Floor Structures. 2014. https://dspace.cvut.cz/handle/10467/54346.

[17] ČSN EN 12350-1: Testing fresh concrete - Part 1: Sampling and common apparatus, 2020.

[18] ČSN EN 12390-1: Testing hardened concrete - Part 1: Shape, dimensions and other requirements for specimens and moulds, 2013.

[19] ČSN EN 12390-2: Testing hardened concrete - Part 2: Making and curing specimens for strength tests, 2020.

[20] ČSN EN 12504-1: Testing concrete in structures - Part 1: Cored specimens - Taking, examining and testing in compression, 2019.

[21] ČSN EN 12390-4: Testing hardened concrete - Part 4: Compressive strength - Specification for testing machines, 2020.

[22] ČSN EN 12390-3: Testing hardened concrete - Part 3: Compressive strength of test specimens, 2020.

[23] ČSN EN 12390-5: Testing hardened concrete - Part 5: Flexural strength of test specimens, 2020.

[24] SN EN 1015-11: Methods of test for mortar for masonry - Part 11: Determination of flexural and compressive strength of hardened mortar, 2020.

[25] ČSN 73 1322: Determination of frost resistance of concrete, 1968.