DE GRUYTER OPEN
RIGA TECHNICAL UNIVERSITY
Construction Science
ISSN 2255-8551 (online)
ISSN 1407-7329 (print)
October 2016, vol. 18, pp. 17–21
doi: 10.1515/cons-2016-0003
https://www.degruyter.com/view/j/cons

Mechanical Properties and Self-Healing Effect of Concrete Containing Capillary Hydro Insulation Admixture

Artūrs Mačanovskis[1], Andrejs Krasņikovs[2], Iluta Spruģe[3], Genādijs Šahmenko[4], Artūrs Lukašenoks[5]
[1–3, 5] *Institute of Mechanics, Riga Technical University*
[4] *Institute of Materials and Structures, Riga Technical University*

Abstract **– Crack formation during exploitation considerably decreases durability of concrete structures. Capillary hydro insulation is an integral crystalline waterproofing system ensuing filling of micro cracks, pores and capillaries with an insoluble crystalline formation. In order to evaluate self-healing effect of this system, fiber concrete beams were initially pre-cracked, then treated with capillary insulation and repeatedly tested under bending. Water permeability and frost resistance tests were also realized in order to evaluate long-term performance of the capillary insulation.**

Keywords **– Crack joining, fiber concrete, permeability, self-healing effect.**

I. INTRODUCTION

Concrete is a basic construction material used for construction of modern residential and industrial buildings, as well as for hydro-technical structures, bridges, tunnels and other important objects. General advantages of concrete are massiveness, fire resistance, high compressive strength and possibility to use local raw materials and industrial by-products for its fabrication. At the same time, negative properties of concrete, such as brittleness, shrinkage during maturing, low tensile strength and low ductility cause cracking of concrete structures during exploitation. Surface and internal cracks increase the risk of water and aggressive chemicals ingress into the concrete body, as a result, degradation processes of concrete structures are considerably accelerating. It is can be mentioned that the cost of repair works could take up to 50 % to 150 % from the initial cost of the structure.

Thus, the task of creating durable structures is associated with limiting the risk of cracking and providing structural impermeability. Concrete thermal and shrinkage deformations, chemical attack, freezing-thawing cycles [1]–[3], deformations of basements, etc. are the main reasons of cracks. Shrinkage is a characteristic property of cement based composites [2], [4]. Concrete is a composite material containing cement matrix and aggregate particles. It is proved theoretically and experimentally that shrinkage of cement matrix causes formation of a system of micro and macro cracks around fibers and aggregate particles [2], [5]. One of the ways to protect concrete constructions against environmental impact is creating surface insulation membrane, which can be based on bitumen, polymer cement or polyurethane. Practical experience shows that traditional surface membranes are subject to ageing and may locally mechanically deteriorate.

Another solution is producing initially impermeable structure and developing the capacity for crack prevention and localization during exploitation. Self-healing materials can be defined as a class of smart materials that have a structurally incorporated ability to repair damage caused by exploitation. The first studies concerning self-healing systems in polymer materials were conducted in 1960th [5]. Usually self-healing effect in concrete is associated with crack closing ability. Nowadays, there are different approaches to achieving crack repair effect, such as crack filling with polymers, salt crystallization from chemical solution or bacteria-based self-healing effect. Comprehensive reviews of self-healing technologies for cementitious materials are summarized in [6]–[8]. Autogenous healing of concrete is induced by intrinsic factors dependent on the composition of the cementitious matrix. Autogenous repair of cracks may be attributed to two mechanisms: hydration of unreacted cement particles and dissolution and subsequent carbonation of calcium hydroxide (product of cement hydration) $Ca(OH)_2$ [8]. It has been proved that processes of autogenous healing can be improved in the presence of water [8].

Use of microcapsules containing sealing compounds is an innovative method of self-healing micro defects in concrete elements. Guerrero et al. applied silica microcapsules filled with epoxy resin and nanosilica functionalized with amine groups for self-healing effect in ultra-high performance concrete during freezing-thawing cycles [9].

Prospective way for creating smart concrete and achieving self-healing effect is the use of active capillary insulation, which ensures the ability of concrete to join micro-cracks. The effect of active capillary insulation technology is based on concrete porosity and permeability. Water serves as a "transport mechanism" by means of which active chemical elements are moved into concrete pores and network of micro-cracks. As a result, cracks and pores are filled and crack flanks are joined with insoluble crystalline formulations [10]. Aniskevich et al. investigated the possibility of creating self-healing laminated composites on the basis of macro-vascular system [11]. Effectiveness of self-healing properties was evaluated by fabrication of laminate specimens and carrying out flexure tests.

Different polymeric and steel fibers are used to improve concrete crack resistance. Effectiveness of polymeric fibers for self-healing properties is shown in the work [12].

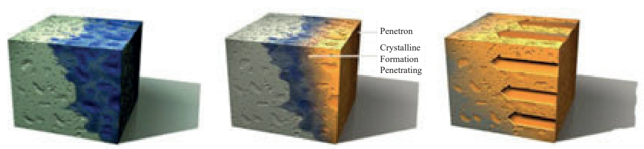
Steel fiber reinforced concrete (SFRC) is a popular material nowadays. Higher tensile strength, ductility and resistance against crack formation are the main advantages of SFRS compared to traditional plain concrete [13]–[17]. The present study proposes combined use of steel fibers and capillary insulation admixtures to achieve self-healing effect and ensure possible improvement of concrete durability.

The aim of this study is to evaluate crack repair effect of capillary insulation by testing bending behavior of concrete beams and checking water permeability of cubic samples.

II. Materials and Methods

A. Materials and Mix Design

Experimental part of this study was done using typical fine-grain fiber concrete mix composition produced from local raw materials. Standard Portland cement CEM I 42.5 N was used as a binding agent, dolomite powder and silica fume micro-fillers were used to provide satisfactory workability to the mix and dense microstructure of the hardened concrete. Two types of sand and crushed granite were used as fine and coarse aggregates for concrete mixes. Capillary insulation material *Penetron Admix* was used as an admixture in concrete mix, material *Penetron* was applied for surface coating.



Moisture in the capillary system of the concrete

Penetron (applied by brush or spray from positive or negative side, as admixture (Penetron Admix) or dry-shake) will penetrate the capillaries, form insoluble crystals and gradually dry out the concrete

Penetrone will continue to spread deeper into the structure permanently protecting concrete against water intrusion and chemical attacks

Fig. 1. Principles of capillary insulation (by *Penetron* company).

Penetron admix is a powder and it was added to the concrete during mixing. This material should be dispersed homogenously throughout the mix. In accordance with producer's information, active components of *the Penetron admix* react with water and mineral components of the cement paste to form insoluble products, which fill cracks, pores and voids up to a width of 400 microns (0.4 mm). In accordance with producer's information, dense microstructure of cement matrix restricts penetration of harmful chemicals in the concrete, however, air can still pass, allowing the concrete to breathe. In the absence of further moisture, the *Penetron admix* components lie dormant. Should moisture reoccur at any time, the sealing process resumes automatically, providing a self-healing effect.

Material *Penetron* is applied as covering for concrete surface. Powder was mixed with water (obtaining homogenous slurry) and was painted on the concrete surface. Active components of *Penetron* penetrate the concrete structure when moisture conditions are provided (Fig. 1). The mechanism of reactions and self-healing effect is the same as in case of using the *Penetron* admix.

In the framework of the experimental part, four mixes of steel fiber reinforced concrete (SFRC) were produced. Proportions of mix compositions in the mixes are summarized in Table I. Samples with dimensions 10 cm × 10 cm × 40 cm were produced for bending test and sample cubes 10 cm × 10 cm × 10 cm – for compressive strength evaluation and water penetration test. Samples were cured in normal conditions (+20 °C in humid environment) and tested at the age >28 days.

TABLE I

Mix Design of Concrete Compositions

Composition, kg/m³	**MIX1**	**MIX2**	**MIX3**	**MIX4**
Portland Cement CEM I 42.5 N	343	343	381	381
Granite break-stone (1/8 mm)	948	948	–	–
Granite break-stone (6/8 mm)	–	–	948	948
Sand quartz (0/1 mm)	105	105	105	105
Sand natural (0.3/2.5 mm)	600	600	600	600
Dolomite powder	90	90	90	90
Silica Fume	25	25	25	25
Superplasticizer (polycarboxilate)	6	6	10	10
Water	214	219	207	207
W/C ratio	0.63	0.64	0.54	0.54
Steel fiber type SW35 (35 mm)	80	80	80	80
Penetron Admix	–	4	–	4
Penetron	–	–	present	–

B. Testing Methods

Bending test was performed for the samples, beams 100 mm × 100 mm × 400 mm, using 4-point bending scheme. Distance between bottom supports L_o was 300 mm, distance between upper force applying points was 100 mm. Samples were loaded with constant load rate 150 N/s. Load F and deflection in the middle point of the prism were experimentally measured and digitally controlled and recorded. Initial test was performed till the first crack appeared, allowing a crack opening of not more than 0.2 mm (visually controlled).

After initial bending test, MIX3 samples were painted with *Penetron* composition and all samples were repeatedly stored in water for 12 days.

Bending strength was calculated using formula: $f_b = FL_o / (BH^2)$, where: B and H are width and high of cross section area of the tested beams (B = 100 mm, H = 100 mm).

Each sample was tested by bending repeatedly. Secondary bending tests were carried out until each specimen crack opening reached more than 6 mm and load-deflection curves were obtained and recorded.

Compression strength was tested in accordance with EN 12390-3. Water permeability test was performed by applying water pressure of 0.5 MPa in one side of cube. Sample was split after 72 hours of water pressure and depth of water penetration was determined (in accordance with EN 12390-8).

III. Results and Discussions

Four experimental mixes of SFRC were produced and tested. Two types of mix granulometry were designed: MIX1 and MIX2 are based on granite break stone 1/8 mm, but MIX3 and MIX4 – 6/8 mm. MIX1 is the reference composition without hydro insulating admixture, but MIX2 and MIX4 contain hydro insulating admixture *Penetron Admix* in the amount of 4 kg/m^3. Samples made out of MIX3 fiberconcrete were covered with penetrating hydro insulation *Penetron*.

C. Compressive Strength and Density

Results of compressive strength and density tests are summarized in Table II. Five cubic samples of each mix were fabricated and tested. Comparing averaged data (Table II) it may be concluded that hydro insulating admixture does not change concrete density, but considerably improves the compressive strength. Increase of the compressive strength is 47 % for MIX2 compared to MIX1 and 27 % for MIX4 compared to MIX3. The mechanism of improving compressive strength can be explained by salts crystallization and denser microstructure formation in cement matrix in case of using a hydro insulating admixture.

TABLE II
Compressive Strength and Density

	Density, kg/m^3	Compressive strength, MPa
MIX2	2385	44.6
MIX3	2385	65.6
MIX4	2365	51.4
MIX5	2390	65.4

D. Initial and Secondary Bending Test Results

The aim of initial bending loading is to induce initial cracks in the tensile area of beams. Initial bending loading of prismatic samples was performed in the linear part of the bending curve. Bending curves are shown in Fig. 3–6. The process of loading was stopped when the first crack opening reached not more than 0.9 mm. The importance of crack opening measurement and analysis of fiber pull out channel in fiberconcrete should be emphasized [18]. In this case crack opening analysis was made using optical lenticular gauge (Fig. 2).

Average values of crack openings are summarized in Table III. The first mix (the reference mix) demonstrates the lowest first step loading maximal bending force (26.76 kN), which corresponds to macro crack formation (0.71 mm). Other compositions that contained hydro insulating admixture (MIX2, MIX3 and MIX4) present higher maximal forces up to 28 %, 12 % and 10 %, correspondingly.

Fig. 2. Crack opening analysis.

E. Secondary Bending Test Results and Analysis of Results

It is worth mentioning that under constant load rate sample loading regime, it is not possible to precisely manage macro crack formation and opening process, evaluating crack opening visually. Results of the secondary bending test after initial crack formation are presented in the same graphs (Fig. 3–6). Averaged (over three samples) curves for first loading (left) and secondary loading are presented in Fig. 7. The lowest values of secondary test bending force (11.1 kN) correspond to reference MIX1 without admixtures. All mixes containing hydro insulating admixture show considerably higher secondary loading curves. In accordance with Table III, improved effects of 89 %, 38 % and 41 % are achieved for MIX2, MIX3 and MIX4, correspondingly. It should be noted that samples from MIX3 (covered with *Penetron* admixture) demonstrated highest dispersion of secondary test results (averaged squared deviation 6.58 kN). It can be explained by dissimilar penetration of the covered insulation into the structure of fiberconcrete.

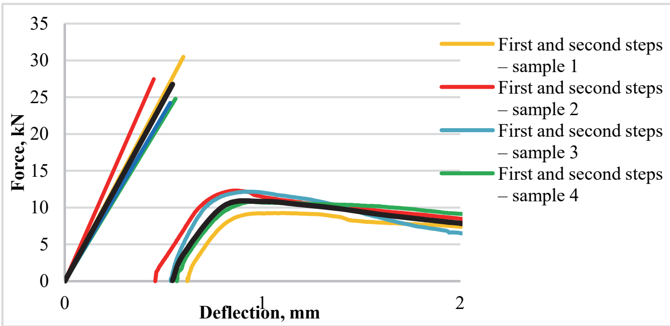


Fig. 3. Bending curves for MIX1. Initial test (pre-bending) left, secondary test right.

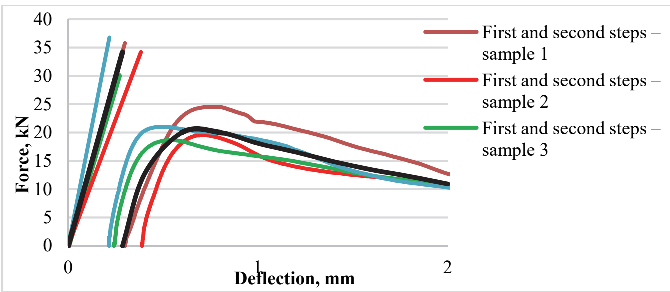


Fig. 4. Bending curves for MIX2. Initial test (pre-bending) left, secondary test right.

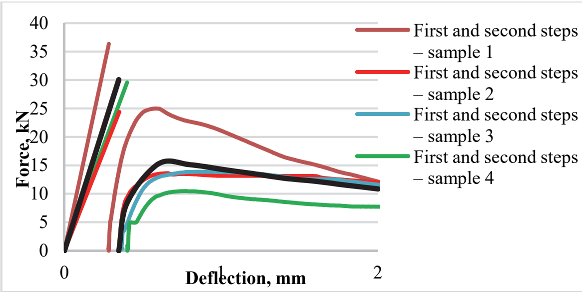


Fig. 5. Bending curves for MIX3. Initial test (pre-bending) left, secondary test right.

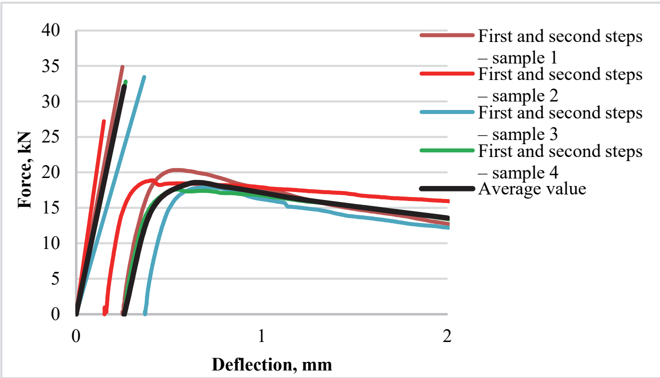


Fig. 6. Bending curves for MIX4. Initial test (pre-bending) left, secondary test right.

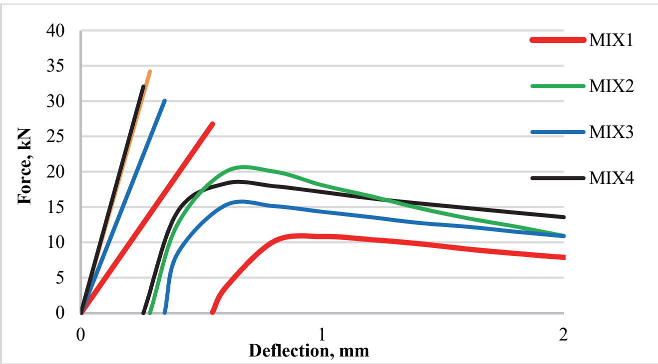


Fig. 7. Average curves for initial test (left) and secondary test.

TABLE III

FIRST AND SECOND BENDING TESTS RESULTS

	First loading maximal force F_1, kN	Average initial crack opening, mm	Second loading maximal force F_2, kN	**F_2 / F_1, %**
MIX1 *S*, kN	26.76 2.87	0.71 0.36	11.10 1.59	**41**
MIX2 *S*, kN	34.20 2.98	0.29 0.07	20.97 2.58	**61**
MIX3 *S*, kN	30.06 4.90	0.87 0.51	15.33 6.58	**51**
MIX4 *S*, kN	29.50 4.44	0.30 0.13	15.71 3.95	**53**

Note. S is average squared deviation.

F. Water Penetration

Results of water penetration after applying water pressure 0.5 MPa during 72 hours are summarized in Table IV, MIX1 is FRC without hydro insulating admixture, MIX2 and MIX4 contain admixture *Penetron Admix*, but MIX3 is covered with Penetron slurry and then cured in moisture conditions. The obtained results show considerable reduction of of water penetration in concrete with hydro insulating admixture (10 mm to 12 mm, comparing to 40 mm for the reference MIX1), see Fig. 8. The effect of densifying concrete micro structure is visible both in the case of admixture (MIX2 and MIX4) and in the case of penetrating from surface (MIX3).

TABLE IV

DEPTH OF WATER PENETRATION

	Depth of penetration, mm	Reduction, percent from REF
MIX1 (REF)	40	0
MIX2	10	75
MIX3	10	75
MIX4	12	70

Fig. 8. Samples after water permeability test.

IV. CONCLUSION

Application of self-healing technologies is a promising way to eliminate crack formation and to improve durability and long-term mechanical properties of concrete.

In the framework of experimental part, reference fiberconcrete samples, as well as samples with penetrating hydro insulating admixture have been produced. It has been found that hydro insulating admixture does not change concrete density, at the same time, it considerably increases the compressive strength (up to 47 %). Bending experiments of fiberconcrete beams proved the ability of capillary insulation admixture to repair cracks developing during initial bending loading. Nearly double increase of secondary loading bending force is achieved in the case of capillary insulating admixture, comparing to the reference sample.

The effect of densifying concrete micro structure was confirmed by water permeability test. Fiberconcrete compositions with hydro insulating admixture demonstrated up to 75 % reduction of water penetration depth, comparing to the reference composition.

Acknowledgement

The financial support of the ESF project No. 1DP/1.1.1.2.0/13/APIA/VIAA/019 "New "smart" nanocomposite materials for roads, bridges, buildings and transport vehicle" is acknowledged.

References

[1] R. Cepuritis and G. Šahmenko, "Frost durability of fibre reinforced concrete: research of effect of steel fibres," in *International congress on durability of concrete ICDC-2012*, 2012, p. 14.

[2] O. Kononova, A. Krasnikovs, R. Stonys, G. Sahmenko, and R. Vitols, "Investigation of influence of nano-reinforcement on the mechanical properties of composite materials," *J. Civ. Eng. Manag*., vol. 22, no. 3, pp. 425–433, 2016. http://dx.doi.org/10.3846/13923730.2015.1106578

[3] V. C. Li, "Postcrack scaling relations for fiber reinforced cementitious composites" *Journal of Materials in Civil Engineering*, vol. 4, issue 1, pp. 41–57. 1992. http://dx.doi.org/10.1061/(ASCE)0899-1561(1992)4:1(41)

[4] P. Lura, M. Wyrzykowski, C. Tang, and E. Lehmann, "Internal curing with lightweight aggregate produced from biomass-derived waste," *Cem. Concr. Res*., vol. 59, pp. 24–33, May 2014. http://dx.doi.org/10.1016/j.cemconres.2014.01.025

[5] Y. M. Malinskii, V. V. Prokopenko, N. A. Ivanova and V. A. Kargin, "Investigation of self-healing of cracks in polymers," *Mekhanika Polim*., vol. 2, pp. 271–275, 1969.

[6] K. Van Tittelboom and N. De Belie, "Self-healing in cementitious materials-A Review," *Materials*, vol. 6, no. 6, 2013. http://dx.doi.org/10.3390/ma6062182

[7] F. P. Bonnaure, A. H. Huibers and A. Boonders, "A laboratory investigation of the influence of rest periods on the fatigue characteristics of bituminous mixes," *Journal of the Association of Asphalt Paving Technologists*, vol. 51, pp. 104–128, 1982.

[8] C. Edvardsen, "Water permeability and autogenous healing of cracks in concrete," *ACI Materials Journal,* vol. 96, issue 4, pp. 448–454, 1999.

[9] A. Guerrero, J. L. García Calvo, P. Carballosa, G. Perez, V. R. Allegro, E. Erkizia and J. J. Gaitero, "An Innovative Self-Healing System in Ultra-high Strength Concrete Under Freeze-Thaw Cycles," in *Nanotechnology in Construction*, 2015, pp. 357–362. http://dx.doi.org/10.1007/978-3-319-17088-6_46

[10] Penetron. *Total concrete protection*. (2014) [Online]. Available: www.penetron.com/downloads/penetron_brochure_en.pdf. Accessed on: July 4, 2016.

[11] A. Aniskevich, S. Vidinejevs, V. Kulakov, and O. Strekalova, "Development of Composites with a Self-Healing Function," *Materials Science*, vol. 21, no. 1, 2015. http://dx.doi.org/10.5755/j01.ms.21.1.5354

[12] T. Nishiwaki, S. Kwon, D. Homma, M. Yamada and H. Mihashi, "Self-healing capability of fiber-reinforced cementitious composites for recovery of watertightness and mechanical properties," *Materials (Basel).*, vol. 7, no. 3, pp. 2141–2154, 2014. http://dx.doi.org/10.3390/ma7032141

[13] ACI Committee 544, "State-of-the-Art Report on Fiber Reinforced Concrete," *ACI Struct. J.,* vol. 96, no. 11, 2002.

[14] A. Krasnikovs and O. Kononova, "Strength prediction for concrete reinforced by different length and shape short steel fibers," *Transport and Engineering. Mechanics*, vol. 31, pp. 89–93, 2009.

[15] A. Krasnikovs, A. Khabaz, I. Telnova, A. Machanovsky and J. Klavinsh, "Numerical 3D investigation of non-metallic (glass, carbon) fiber pull-out micromechanics (in concrete matrix)," *Transport and Engineering. Mechanics*, vol. 33, pp. 103–108, 2010.

[16] O. Kononova, V. Lusis, A. Galushchak, A. Krasnikovs and A. Machanovskis, "Numerical modeling of fiber pull-out micromechanics in concrete matrix composites," *Journal of Vibroengineering*, vol. 4, issue 4, pp. 1852–1861. Dec., 2012.

[17] A. Krasnikovs, A. Khabbaz, G. Sahmenko and V. Lapsa, "Glass and Carbon Fiber Concrete Micro-mechanical and Macro-mechanical Properties," *Transport and Engineering. Mechanics*, vol. 28, pp. 132–140, 2008.

[18] A. Macanovskis, V. Lusis and A. Krasnikovs, "Crack Opening Investigation in Fiberconcrete," *International Journal of Civil, Architectural Science and Engineering,* vol. 8, no. 4, pp. 102–109, 2014.

Artūrs Mačanovskis, Dr. sc. ing., Researcher at the Institute of Mechanics, Riga Technical University. A. Mačanovskis is an author and co-author of 25 scientific publications and 3 patents. Takes active part in various scientific conferences (over 20 presentations) on composite materials.
Address: Ezermalas iela 6, Riga, LV-1006, Latvia
E-mail: artursmacanovskis@inbox.lv

Andrejs Krasņikovs, Dr. sc. ing., Professor at the Institute of Mechanics, Head of Concrete Mechanics Laboratory, Riga Technical University. Full member of the Latvian Academy of Sciences. Vice-President of the Latvian Academy of Sciences. A. Krasņikovs is an author and co-author of 195 scientific publications, 30 patents and 3 learning aids. A. Krasņikovs is a member of ASME, ESCM, LNMC, LMRS and Concrete Society of Latvia.
Address: Ezermalas iela 6, Riga, LV-1006, Latvia
Phone: +371 294 365 18; Fax: +371 670 891 59.
E-mail: akrasn@latnet.lv

Iluta Spruģe, M. sc. ing., Institute of Mechanics, Riga Technical University.
Address: Kaļķu iela 1, Riga, LV-1658, Latvia
E-mail: iluta.spruge@inbox.lv

Genādijs Šahmenko, Dr. sc. ing., Leading Researcher, Institute of Materials and Structures, Riga Technical University.
Field of research: High performance concrete, ecological building materials, foam concrete, non-destructive testing.
Address: Kaļķu iela 1, Riga, LV-1658, Latvia
E-mail: genadijs.sahmenko@rtu.lv

Artūrs Lukašenoks, PhD student, Faculty of Civil Engineering, Concrete Mechanics Laboratory, Riga Technical University. A. Lukašenoks is an author and co-author of 4 scientific publications.
Address: Ezermalas iela 6, Riga, LV-1006, Latvia
E-mail: Arturs.Lukasenoks@rtu.lv