Rannsókn á sprautusteypu með umhverfisvænum basalt trefjum í stað notkunar á plasttrefjum

March 2019

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Nýsköpunarmiðstöð Íslands

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Rannsóknarstofa byggingariðnaðarins

Reykjavik University

School of Science and Engineering

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Rannsóknarsjóður Vegagerðarinnar styrkti rannsóknarverkefnið

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Introduction

Purpose of this project was to design sprayed concrete with convenient properties and lower environmental and pollution impact on nature. Laboratory testing of several types of sprayed concrete with various types of fibers reinforcement was used as a tool for verifying our idea, that sprayed concrete with basalt fibers might dispose of better properties than sprayed concrete with steel or plastic fibers.

Work frame

1) Selection and evaluation of input materials for the production of sprayed concrete. An integral part will be a selection of basalt, steel and plastic fibers for testing.

Completed:

Selection and evaluation of the input materials is one of the subjects described in the poster for UArctic workshop: „Mineral Research in the Arctic“ held in Tromsø, Norway. Title of the poster is „Investigation of sprayed concrete with environmentally friendly basalt fibers for tunnel linings“, see Appendix 1. Furthermore, selection and evaluation of input materials is described in the article which is going to be published within fib SYMPOSIUM 2019: Concrete - innovations in materials, design and structures, Krakow, Poland, May 2019. The title of the article is: „Influence of environmentally friendly basalt fibers on early-age strength of sprayed concrete “; see Appendix 3.

2) Design of sprayed concrete without and with various types of fibers. Concrete used in practice will inspire the design of our mixes for experimental work in the laboratory. All laboratory tests on designed concrete going to be performed according to ÍST EN 14487-1:2005 Sprayed concrete –Part 1: Definition, specifications, and conformity.

Completed:

Design method is one of the subjects described in the poster for UArctic workshop: „Mineral Research in the Arctic“ held in Tromsø, Norway. Title of the poster is „Investigation of sprayed concrete with environmentally friendly basalt fibers for tunnel linings“, see Appendix 1. The research results published within UArctic workshop: „Mineral Research in the Arctic“ were extended and republished under the same name within conference Rannsóknaráðstefna Vegagerðarinnar 2018 held in Reykjavik, Iceland. The poster for conference Rannsóknaráðstefna Vegagerðarinnar 2018 is attached as an Appendix 2.

Furthermore, design and development of laboratory sprayed concrete are described in the article which is going to be published within fib SYMPOSIUM 2019: Concrete - innovations in materials, design and structures, Krakow, Poland, May 2019. The title of the article is: „Influence of environmentally friendly basalt fibres on early-age strength of sprayed concrete“, see Appendix 3.

3) Design of the mixes will be followed by practical testing of mixes and their properties in fresh state as density, fiber content (ÍST EN 14488-7:2006), and consistency when using wet-mix method (EN 12350-2 or EN 12350-5) if possible to measure.

Completed:

Properties of the fresh sprayed concrete such as density, workability and workability loss were tested. Workability and workability loss of mixes with various dose of basalt fibers were evaluated based on rheological data measures by Viscometer 6 from ConTec. Properties of fresh concrete are described in the article which is going to be published within fib SYMPOSIUM 2019: Concrete - innovations in materials, design and structures, Krakow, Poland, May 2019. The title of the article is: „Influence of environmentally friendly basalt fibres on early-age strength of sprayed concrete“, see Appendix 3.

4) Between testing of fresh concrete and harden concrete after 28 days might take place strength testing of young sprayed concrete which depends on obtaining testing equipment. Testing according to prEN 14488-2

Completed:

Shotcrete Penetrometer was bought from the budget of this project. It is testing equipment for testing the compressive strength of the initial stage of young sprayed concrete according to EN ISO 14488-2 (Method A).

Test procedures and results are one of the subjects described in the poster for conference Rannsóknaráðstefna Vegagerðarinnar 2018 held in Reykjavik, Iceland. Title of the poster is „Investigation of sprayed concrete with environmentally friendly basalt fibers for tunnel linings“, see Appendix 2. Furthermore, compressive strength testing of young sprayed concrete is described in the article which is going to be published within fib SYMPOSIUM 2019: Concrete - innovations in materials, design and structures, Krakow, Poland, May 2019. The title of the article is: „Influence of environmentally friendly basalt fibres on early-age strength of sprayed concrete“, see Appendix 3.

5) Several tests performed on hardened concrete will be selected from the standard for testing of sprayed concrete, e.g., density, ultimate flexural strength, bond strength and compressive strength. Freeze-thaw resistance is very important in Icelandic climatic conditions and will be performed according to CEN/TR 15177: 2006.

Completed:

Tests on hardened concrete were performed on various types of samples, mixes and after various ageing length. Within this project, three series of mixes were tested. The first series was designed for laboratory concrete sprayer consists of Icelandic aggregates with maximum particle size 4 mm and basalt micro-fibers in dose 0, 4, 6 and 8 kg/m^3. The second series contained Norwegian aggregates with maximum particle size 4 mm and basalt micro-fibers in same dose 0, 4, 6 and 8 kg/m^3. Those mixes were used for evaluation of density and rheological properties of fresh concrete and subsequently cast for evaluation of flexure and compressive strength after 24 hours from the beginning of mixing. Mixes designed and used for laboratory sprayer and rheological properties evaluation contained only basalt micro-fibers as the laboratory sprayer so as Viscometer 6 form ConTec were not able to properly spray and mix mixes with steel or polymer fibers. Due to this technical limitation, the third series consisted of mixes with basalt micro and macro fibers, steel fibers and polymer fibers which were prepared in a laboratory mixer and cast as standard concrete. Those mixes were exclusively prepared for hardened concrete properties testing, namely density, freeze-thaw resistance, flexure and compressive strength.

Series for testing the hardened concrete properties consist of two types of concrete: normal strength concrete (NSC) and high strength concrete (HSC). Each type of concrete was prepared with two versions, one with steel (S) and polymer (P) fibres and second with micro (MIB) and macro (MAB) basalt fibres. The dose of the fibres was controlled by volume as the density of all four types of fibres differ significantly. Hardened concrete properties of both series are presented in Table 1, Figure 1 and Figure 2.

Table 1: Properties of hardened concrete; series HSC and NSC

Concrete type	Fibres type	Density 28 days [kg/m^3]	Flexure strength 28 days [N/mm^2]	Compressive strength 2 days [N/mm^2]	Compressive strength 28 days [N/mm^2]	Compressive strength 90 days [N/mm^2]	Freeze-thaw resistance: scaling after 56 cycles [kg/m^2]
HSC	S+P	2554	-	60,8	86,1	98,7	0,02
HSC	MIB+MAB	2439	10,6	59,6	84	86,7	0,03
NSC	S+P	2366	7,3	29,8	42,5	46,4	0,13
NSC	MIB+MAB	2436	6,1	29,7	43,9	47,9	1,89

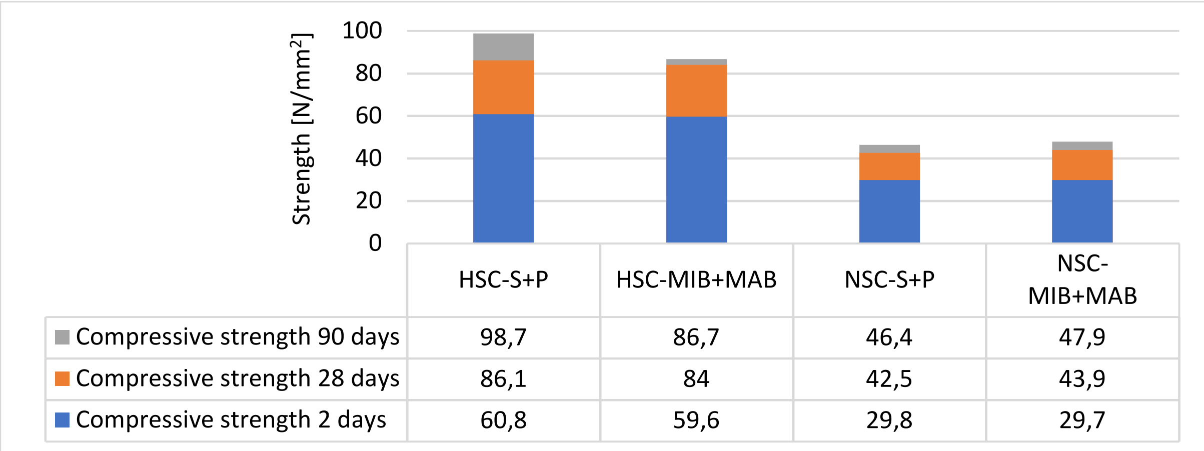
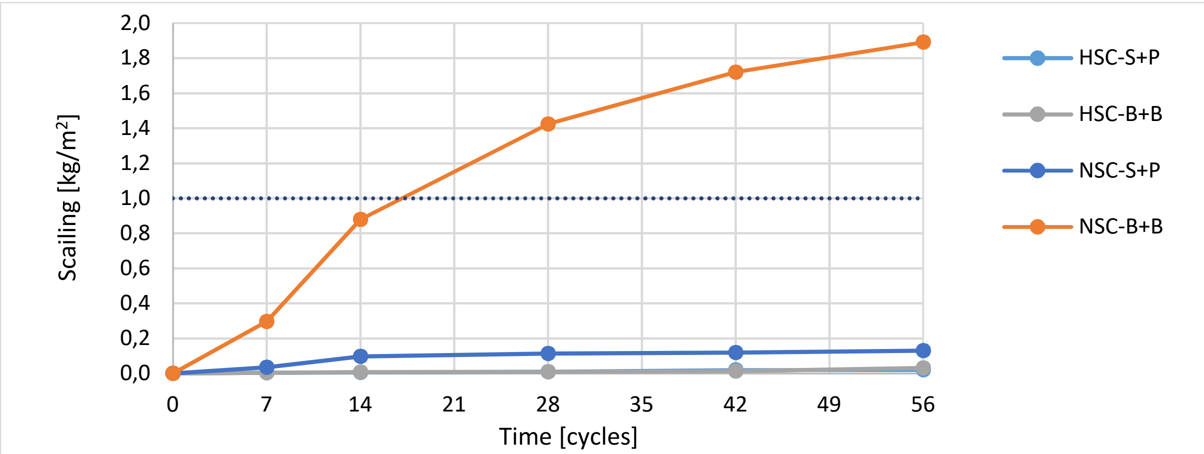


Figure 1: Compressive strength results from hardened concrete testing of series HSC and NSC



*Maximum allowed scaling according to Icelandic building regulation

Figure 2: Freeze-thaw resistance results from hardened concrete testing of series HSC and NSC

From the data recorded during the laboratory testing is significant that basalt fibres give very similar result of compressive strength as steel fibres in combination with polymer fibres in both cases, only exception is higher gain of compressive strength of HSC-S+P after 90 days in comparison to HSC-MIB+MAB. Freeze-thaw resistance of both samples of HSC and NSC-S+P are sufficient and fulfilling limits according the Icelandic building regulations. Unfortunately, the sample NSC-MIB+MAB is failing the freeze-thaw resistance as the scaling is close to 2 kg/m^3. The sample was inspected under microscope and there was a visible white line around the individual aggregate particles which is most probably cased by overdose of plasticizer. Rather visible formation of cement milk was recorded also during the fresh concrete testing of NSC-MIB+MAB. Repetition of tests performed on mix NSC-

MIB+MAB is necessary to obtain valuable results and be able to draw conclusion of the performance of basalt fibres in NSC exposed to freezing and thawing cycles.

6) Eventual redesign of sprayed concrete mixes based on results from testing of fresh and hardened concrete. Parameters which could be taken into account are a dose of fibers, amount of cement, water/cement ratio or another parameter.

Completed:

Redesign of the mixes took place, and it is described and discussed in the poster for conference Rannsóknaráðstefna Vegagerðarinnar 2018 held in Reykjavik, Iceland. Title of the poster is „Investigation of sprayed concrete with environmentally friendly basalt fibers for tunnel linings“, see Appendix 2. Within this part of research sprayed concrete mixes were tested and various types of aggregates had to be investigated. The first used type of aggregates were Icelandic aggregates in a fraction 0-8 mm as producer stated that maximum particle size for the laboratory sprayed is 8 mm. During the testing of the first mixes was decided to reduce the maximum particle size to 4 mm as the spraying process was difficult and the nozzle was frequently plugged and an uneven sprayed concrete layer formed. The same aggregates were sieved to fraction 0-4 mm and tested again. The mix was still not optimal as this type of aggregates are crushed and contain a low share of fines, and have high water absorption. Base on this issue, the second type of Icelandic aggregates in a fraction 0-4 mm with higher content of fines, and more rounded particles as the sand is mined were selected. Furthermore, the dose of water and accelerator was adjusted during the testing of mixes with various basalt fiber dose.

Another adjustment of mixes took place during the testing of rheological properties of fresh concrete. Along the increasing basalt fiber dose, air content in concrete mixes was rising. Rheological properties measurements were significantly influenced by inconstant air content and therefor defoamer was used. Density measurements of fresh concrete served as a control tool for constant air content in all mixes. Results from rheological testing and adjustment of the air content in the fresh concrete are presented in the article which is going to be published within fib SYMPOSIUM 2019: Concrete - innovations in materials, design and structures, Krakow, Poland, May 2019. The title of the article is: „Influence of environmentally friendly basalt fibers on early-age strength of sprayed concrete“, see Appendix 3.

7) Environmental impact evaluation going to be based on technical data from the production of fibers, EPD database and traditionally used techniques for handling rebound from spraying and washing of residues from concrete mixing tracks.

Not completed:

Due to the reduction of budget, evaluation of environmental impact of sprayed concrete with basalt fibers and comparison to presently used steel and polymer fibers was not performed.

Conclusion

The project was focused on properties of concrete, specifically sprayed concrete with the addition of basalt fibres and their impact on fresh and hardened state concrete properties. There were 7 work packages proposed, and six of them were performed. The last work package “Environmental impact of sprayed concrete” was not completed due to a reduction of the project budget.

Results showed improvement of fresh and hardent stated concrete with basalt fibres and it could be concluded that basalt fibres are very convenient candidate for replacement of traditionally used steel and polymer fibres. Cooperation with construction company form Iceland was established base on the results obtained within this project. Company is interested in further testing of basalt fibres and possibly large-scale testing will take place in near future.

Appendix 1: Poster entitled „Investigation of sprayed concrete with environmentally friendly basalt fibers for tunnel linings“, UArctic workshop: „Mineral Research in the Arctic“, Tromsø, Norway, June 2018.

UArctic Workshop: "Mineral Research in the Arctic"

Investigation of sprayed concrete with environmentally friendly basalt fibers for tunnel linings

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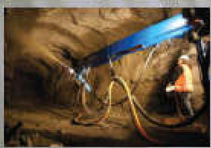
Introduction

An important part of the mining industry are temporary and permanent structures which are required for safety features and technical background of the whole mining process. The safety issues are significant during the mining, and proper adjustment of the walls of the pit is one of the main safety parameters. Walls of newly explored mines are commonly supported by lining with various parameters depending on the size of the pit, excavated mineral raw material and all other details. The lining could be built from wood planks, sprayed concrete or other material and techniques. In the larger underground mines are commonly used sprayed concrete linings as the application is faster and more simple than other types of linings.




A brief overview of the geology of Icelandic

Iceland is geologically very young and has been formed about 24 million years ago, but the oldest rock exposed to the surface is about 14 – 16 million years old. Igneous rocks represent about 75% of all surface exposed rocks and majority is mafic magma. Mafic magma is melting at temperatures above 1100°C and is relatively low in silica (< 52%) and rich in magnesium, iron and calcium. Sediments constitute the remaining 25% of the rocks exposed to the surface. As basalt is vulcanic extrusive rock and constitutes 90% of all rock types in Iceland, it is essential to investigate its use for various industrial purposes, especially in building industry. Currently is basalt used for the production of rock wool for thermal insulation for buildings and other industrial machinery. The factory uses electric melting with a supply of electrical energy from the hydroelectrical and geothermal power plant, and main raw materials for the production of rock wool are local basalt sand and crushed seashells. The chemical composition of basalt rock for rock wool production is not as strict as for production of single fiber. Basalt in Iceland is rather young, and origin from different vulcanos and eruptions which results in a high variety of chemical compound share in basalt. Within GREENBAS project was explored and sampled in total 154 areas and high variety of chemical composition of basalt rock was obtained.

Sprayed concrete

Sprayed concrete is a special type of concrete applied on the based layer, for tunnelling on bad rock, by spraying and therefore the concrete mix requires different treatment than concrete for standard applications. One of the most important properties of the sprayed concrete is the amount of rebound during application, setting time and flexure strength and bond strength of hardened concrete. Amount of rebound (fallout of concrete while spraying) for wet spraying method is from 5 to 15% and usually is washed away from the tunnel into surrounding area. This fact is a very important aspect of the used type of sprayed concrete. Fresh concrete with steel or polymer fibers is way less ecologically desirable than concrete with no fibers content. Above this all, polymer fibers are the worst used fibers due to their long disintegration half-time.

Laboratory testing of various types of sprayed concrete

Part of the GREENBAS project was also focused on the application of basalt fiber composites and chopped basalt fibers into concrete and concrete elements. Results from testing of concrete with chopped basalt fibers were promising especially with the increase of flexural toughness (1). These results seem convenient for application of chopped basalt fibers into sprayed concrete.

Experimental work consists of a selection of suitable raw materials like cement, aggregates concerning maximum grain size and fines content, water, additions and admixtures. It is convenient to consider use of suplementary cementious materials to reduce cement content dose which varies between 380 to 480 kg/m3. In over case, we used basalt fines and aggregates with maximum grain 4 mm. Hardening accelerator for faster hardening and plasticizer for obtaining more workable mix are two most common used admixtures in sprayed concrete. Within laboratory testing, we used the only plasticiser for the better workability of the mix and easier spraying by laboratory sprayer.

Design of sprayed concrete was inspired by conventionally used sprayed concrete mix designs but converted to laboratory scale. Laboratory sprayer can spray concrete with maximum particle 8 mm and as the concrete mix is forced only by its weight towards the sprayed outlet more flowable mix is required to omit segregation of bigger particles. The presence of basalt fibers while spraying has not caused any blocking of the nozzle and rather helped to avoid segregation of the mix.

Concrete without fibers was made as reference mix and then mixes with various doses of basalt fibers were prepared. At the moment only photo documentation, respectively visual evaluation and thickness of sprayed layer were examined. Sprayed concrete was applied on tilted board. The angle of inclination was 20 degree. Prepared mixes haven't wary only by basalt fiber content but also composition itself was investigated, and segregation, stability and amount of rebound were recorded.

Conclusion

Sprayed concrete was designed and tested in laboratory condition. Designed mixes were applied on inclined plane and segregation, amount of rebound, the thickness of layer and stability of the mix was recorded. Sprayed with basalt fibers was more compact and performed better in the sense of the constant layer and lower segregation. Further testing will be focused on early age strength and properties of hardened concrete.

Why basalt fibers?

Currently, many research teams around the world are investigating problematics focused on fiber reinforced concrete with various types of fibers including also basalt fibers. Basalt fibers dispose of many convenient mechanical and physical properties, and it might be stated, that they are more durable in aggressive conditions than glass fibers and significantly cheaper than carbon fibers. Basalt fibers are used not only as a dispersed reinforcement but also composite basalt reinforce rebars are produced.

Basalt rock requires a lower melting temperature of the raw material in comparison to other materials like iron ore or glass which are used for the production of fiber for dispersed reinforcement in concrete. Polymer fibers do not require high melting temperature, but they are less environmentally friendly.

One study was focused on a comparison of basalt and glass fibers and their energy efficiency differences of fibre production. Results showed that basalt fibers have same heat and electricity consumption but there is a absence of process emissions, usage of boric acid, wast and much lower required amount of epoxy resin. In total relevant contribution of 10 considered factors riched 80% in case of basalt fibres while it was 100% for glass fibres. Also, resource depletion and water depletion is significantly higher in connection of glass fibres. Requirement of boric acid for glass production is one of the main drawback in sense of the environmental profile.

Chemical composition of basalt rock [1]

Chemical compound	Share in basalt rock [%]
Silicon dioxide (SiO_2)	48.8 - 52.8
Magnesium oxide (MgO)	6.2 - 16.0
Irone oxide (FeO + Fe_2O_3)	7.3 - 13.3
Calcium oxide (CaO)	8.6
Aluminium oxide (Al_2O_3)	14.0 – 17.5

Other chem. compounds presented in lower shares: sodium oxide, potassium oxide, titanium oxide, phosphourus pentoxide.

Figure 1 Comparison of sprayed concrete and sprayed concrete with basalt fibres

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Appendix 2: Poster entitled „Investigation of sprayed concrete with environmentally friendly basalt fibres for tunnel linings“, Rannsóknaráðstefna Vegagerðarinnar 2018, Reykjavik, Iceland, November 2018.

Rannsóknaráðstefna Vegagerðarinnar 2018

Investigation of sprayed concrete with environmentally friendly basalt fibers for tunnel linings

Rannsókn á sprautusteypu með umhverfisvænum basalt trefjum í stað notkunar á plasttrefjum

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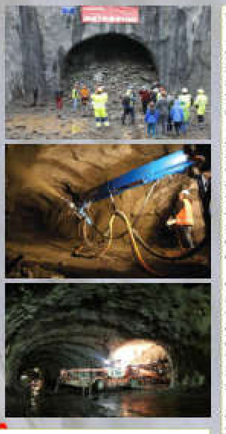
Introduction

Icelandic landscape has a volcanic origin, and the coastline is full of steep hills, and deep fjords which make the development of transport network difficult. Mountain overpasses and long roads curling around coastlines of peninsulas are commonly extremely complex and rather expensive to maintain during the winter period. Tunnels contribute to safer transportation and reduce the time and length of journeys.

At the moment there are eleven open road tunnels in Iceland, and five of them have been open since the beginning of the 21st century. Furthermore, two new road tunnels are under construction. These numbers indicate the rapid development of road infrastructure which could be driven by a constantly rising number of tourists heading to.Iceland. Furthermore, it is important to mention the spillway tunnel system which is part of the Kárahnjúkar Hydropower Plant, and it is the longest tunnel in Iceland.

Most common material for tunnel lining is sprayed concrete due to its relatively easy and fast application, and low price in comparison to the other materials used for tunnel lining. Concrete tunnel lining is beneficial for larger tunnels like road, railway or big mining pits. Wood planks, steel frames and steel plates are usually used for the lining of.smaller mining pits or pedestrian tunnels. Sprayed concrete has lately replaced the traditional methods of lining tunnel profiles and become very important in stabilising the excavated tunnel sections. Various types of dispersed fibers could be used to improve properties of plain sprayed concrete, for example, brittleness and limited tensile and bending strength.

This study is focused on the development of sprayed concrete with environmentally friendly basalt fibers. Basalt fibers are a relatively new type of fibers which does not have stable use in concrete technology yet, but this is about to change with rising emphasis on environment-friendly materials. Currently, the most used fibers for dispersed fiber reinforcement are polymer macro or micro fibers and steel fibers which are either unecological or causing high carbon footprint.



Sprayed concrete

Sprayed concrete is a special type of concrete applied by spraying on the based layer, in case of tunnelling on bad rock. Different rules apply while designing a sprayed concrete, for example, higher content of fines, maximum aggregates size or necessity of accelerator agent addition. One of the most important properties of the sprayed concrete is the amount of rebound during application, setting time and flexure strength and bond strength of hardened concrete. Amount of rebound (fallout of concrete while spraying) for wet spraying method is from 5 to 15% and usually is washed away from the tunnel into surrounding area. This fact is a very important aspect of the used type of sprayed concrete. Fresh concrete with steel or polymer fibers is way less ecologically desirable than concrete with no fibers content. Above this all, polymer fibers are the worst used fibers due to their long disintegration half-time.

Figure 1 a) Krampe harex PP-fibers; b) Basaltex basalt fibres; c) various types of macro and micro fibres

Laboratory testing of sprayed concrete

Experimental work consists of a selection of suitable raw materials like cement, aggregates concerning maximum grain size and fines content, water, additions and admixtures. It is convenient to consider the use of supplementary cementitious materials to reduce cement content dose which varies between 380 to 500 kg/m³. Within this testing, basalt fines were not added to omit more than one variable in mixes and also because used aggregates had high fine content which contributed to compact mix. Hardening accelerator admixture for faster hardening and plasticizer for obtaining more workable mix are two most common used admixtures in sprayed concrete.

Design of sprayed concrete was inspired by conventionally used sprayed concrete mix designs but converted to laboratory scale. Laboratory sprayer supplied by Fishstone GFRC can spray concrete with maximum particle 4 mm and as the concrete mix is moved only by its weight towards the sprayed outlet more flowable mix is required to omit blocking of the outlet. The presence of basalt fibers while spraying has not caused any blocking of the nozzle and rather helped to avoid segregation of the mix.

Concrete without fibers was made as reference mix and then mixes with 4, 6 and 8 kg of basalt fibres per 1 m³ were prepared. Sprayed concrete was applied on tilted board which was inclined under 20 degree. Cement content, aggregate dose and amount of superplasticizer were kept constant, and a dose of water with accelerator slightly varied due to the addition of fibers. Shotcrete penetrometer from Mecmesin was used for measurements of early age strength in the range of 0 to 1,2 MPa.

Figure 3: Images of the surface of test samples with various dose of basalt fibres content.

Conclusion

Sprayed concrete was designed and tested in laboratory condition, and therefore some changes had to be done to regular mix design for field sprayed concrete. Maximum aggregates grain size was 4 mm, and basalt fibers dose 0, 4, 6, 8 kg/m³ which required a slight rising of water and accelerator content. Measurements of early age strength by penetrometer was performed 6, 20, 40 and 60 min after termination of spraying. Sample with basalt fibers were more compact and performed better in the sense of the constant layer and lower segregation. It could be stated that early age is gained faster with a higher dose of basalt fibers. All tested samples were classified into class J2 according to ÍST EN 14487-1Further testing will be focused on properties of hardened sprayed concrete tested according to European standards.

Why basalt fibers?

Currently, many research teams around the world are investigating problematics focused on fiber reinforced concrete with various types of fibers including also basalt fibers. Basalt fibers dispose of many convenient mechanical and physical properties, and it might be stated, that they are more durable in aggressive conditions than glass fibers and significantly cheaper than carbon fibers.

A study conducted by Vito NV [1] was focused on a comparison of basalt and glass fibers and their energy efficiency differences during the production. Results showed that basalt fibers have the same heat and electricity consumption, but there is an absence of emission processing, usage of boric acid, amount of waste and much lower required amount of epoxy resin for composites. In total relevant contribution of 10 considered factors riched 80 % in case of basalt fibers while it was 100 % for glass fibers. Also, resource depletion and water depletion is significantly higher in connection of glass fibers. The requirement of boric acid for glass production is one of the main drawbacks in the sense of the environmental profile.

Basalt rock has a lower melting temperature than iron ore or silica sand which are raw materials for the production of fibers for dispersed concrete reinforcement. Polymer fibers do not require high melting temperature, but they are less environmentally friendly. Input materials for the production of basalt fibers could be exclusively basalt rock or bland of basalt rock with other minerals. Production of the continuous filament is more sensitive than the production of rock wool, and therefore the chemical composition of input materials has to be closely monitored, and also not every basalt rock is suitable.

Icelandic basalt is young mineral, and its chemical composition is commonly more variable, which is not suitable for presently used technologies for continuous filament production. Nevertheless, this might change due to innovations of presently used technologies for basalt continuous filament production and allowed less strict criteria on input raw material.

Table 1: Properties of various material based fibers

	Krampe Harex PM12/18 [2]	Basaltex BCS17-25.4-KV13 [3]
Material type	Polyplopylene	Basalt
Diameter [μm]	18 ± 10 %	17
Length [mm]	12 ± 10 %	24.4
Density [kg/m³]	900	2 670
Degradation temperature [°C]	not specified	600 - 700
Melting point [°C]	170	1 350
Tensile strength [N/mm²]	300	4 840
Young´s modulus [N/mm²]	1 550 ± 16 %	88 000 ± 5%

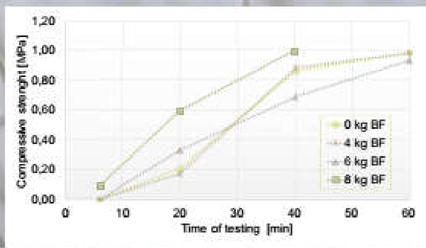


Figure 2: Comperison of early age compressive strength gain of sprayed concrete with 0, 4, 6 and 8 kg of basalt fibres tested by penetrometer.

Resalt evaluation

All prepared mixes prove satisfying behaviour in the fresh state and also during the early phase of ageing. The consistency of fresh sprayed concrete was getting more compact and little bit stiffer with rising amount of basalt fibers. To omit difficulties with spraying slightly higher water content and accelerator dose was added. Testing of early age compressive strength according to ÍST EN 14488-2 Method A was performed 6, 20, 40 and 60 min for termination of spraying. Sample with 8 kg of basalt fibres was not measurable at 60 min because the strength exceeded measurable range of penetrometer. In the sample with 6 kg of basalt fibers were visible small fiber agglomeration caused by imperfect mixing procedure.

References

[1] K. Boonen, G. Janssens and S. Manshoven; Summary report on the environmental potential of basalt fibres versus glass fibres. Vito NV, 2017.
[2] Technical Data Sheet, https://www.krampeharex.com/typo3temp/pdf/PDB_KrampeHarex-Kunststoffaser-PM_12_18.pdf?1491462084
[3] Technical Data Sheet, http://www.basaltex.com/files/cms1/BAS220_1270_P.pdf

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Nýsköpunarmiðstöð Íslands

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REYKJAVIK UNIVERSITY

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Appendix 3: Article entitled „Influence of environmentally friendly basalt fibres on early-age strength of sprayed concrete", fib SYMPOSIUM 2019: Concrete - innovations in materials, design and structures, Krakow, Poland, May 2019.

INFLUENCE OF ENVIRONMENTALLY FRIENDLY BASALT FIBRES ON EARLY-AGE STRENGTH OF SPRAYED CONCRETE

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Abstract

Sprayed concrete is widely used for the stabilisation of newly bored walls or as tunnel lining. Nowadays there is a tendency to use dispersed fibre reinforcement to improve its properties and omit the installation of steel nets as a time-consuming process. Most common fibres for concrete are steel and synthetic fibres which are not considered ecological due to their production or polluting effect on nature. Basalt microfibres and composite macrofibres are a relatively new product on the market and seem like a very convenient and eco-friendly solution for the replacement of steel and synthetic fibres. The influence of basalt fibres on properties of fresh and hardened cementitious materials was analysed within this study. Basalt fibres were applied in dose 0, 4, 6 and 8 kg per cubic meter. Their influence on rheological properties of fresh mortar was evaluated by Viscometer 6 from ConTec. Furthermore, 24 hours compressive and flexure strength were examined. The second part of the study is dealing with early age compressive strength of sprayed concrete. Results showed improvement of both fresh and hardened properties of both tested cementitious materials. As the most suitable basalt fibre dose was selected 4 kg per cubic meter, which disponed by satisfying properties and is economical.

Keywords: Basalt fibres, sprayed concrete, early age strength, penetrometer.

1. Introduction

Nordic countries have an exceptionally diverse landscape characterised by steep hills and deep fjords, and due to this fact, the development of the transport network is a challenging task. To better imagine it, the air length of Norway from NNS to SSW is 1.752 km, but the total coastal line length is estimated at 21.925 km. The main traffic corridor is mostly situated inland, but the northern part is mostly curling around the coastlines of peninsulas. Today there is 18.199 bridges, for a total bridge length of 446 km and over 900 road tunnels with a total length exceeding 750 km. Iceland, which is about three times smaller in area than Norway, has currently 11 road tunnels with a total length of approximately 65,3 km, with five of them open since the beginning of the 21st century. Furthermore, two new road tunnels are under construction. These numbers indicate the rapid development of road infrastructure, where our research focused on sprayed concrete with environmentally friendly basalt fibres could be utilized.

The most common material for tunnel lining is sprayed concrete due to its relatively easy and fast application, and low price in comparison to the other materials used for tunnel linings. Concrete tunnel lining is beneficial for larger tunnels like road, railway or big mines. Wood planks, steel frames and steel plates are usually used for the lining of smaller quarries or pedestrian tunnels. Sprayed concrete has lately replaced the traditional methods of lining tunnel profiles and become very important in stabilising the excavated tunnel sections (Aldrian 2011). Various types of dispersed fibres could be used to improve the properties of plain sprayed concrete, for example, brittleness and limited tensile and bending strength (Baláž et al. 2017).

This study is focused on the development of sprayed concrete with environmentally friendly basalt fibres. Basalt fibres are a relatively new type of fibres on the market, which do not have extensive use in concrete technology yet, but this is about to change with the rising emphasis on environment-friendly materials (Ralegaonkar et al. 2018). Currently, the most commonly used fibres for dispersed fibre reinforcement are polymer macro or micro fibres and steel fibres, both of which are not eco-friendly, by taking a long time to decompose and causing a high carbon footprint respectively.

Figure 1. Tunnel work documentation: a) tunnel front secured by sprayed concrete, b) example of the sprayed concrete device, c) tunnel drilling works.

2. Sprayed concrete

Sprayed concrete is suitable for structures where conventional concrete finished with formwork cannot be applied. Main limitations for the installation of formwork is the necessity of a work area and flatness of the based surface. Both these limitations could be omitted, as the required area is only space for the spraying device manipulation, formwork is not necessary, and an uneven surface is a positive contribution to the greater contact zone. The thickness of the sprayed concrete layer is controlled by the operator of the sprayer device. The surface of the sprayed concrete is usually rough, and if a smooth surface is required, steel trowels could be used.

There are two types of sprayed concrete application methods based on the state of the concrete (Sika, 2011), (Hilar et al. 2008). The first -and older- type is dry sprayed concrete, which is supplied as a dry mix of cement and aggregates or other additions, and water with admixtures are added in the spraying nozzle. This type is convenient for construction works in remote places where it is difficult or impossible to supply ready-mix concrete from a concrete plant or smaller scale spraying works. The disadvantage of dry spraying is a higher amount of rebound of up to 25 vol. % and higher production of dust during the spraying. The second application technique is wet sprayed concrete, which uses ready mix concrete delivered by a mixer truck, or directly from the temporary concrete plant at the construction site and in the nozzle is added only shotcrete accelerator. Rebound of the wet sprayed concrete method is in the range from 5 to 15 vol. %, and the level of dust pollution is lower, which contributes to the more frequent use of this method. Dispersed fibre reinforcement could be added in the case of both application methods. Fibres could be already mixed in dry or wet concrete or blended into the concrete through a special chopping device attached to the nozzle.

Concrete is pumped into the spraying nozzle under pressure and material is shot on to the base surface in layers, which form compact shells after hardening. The raw materials for sprayed concrete are aggregates, cement, water and admixtures which are obligatory. Optional components are supplementary cementitious materials and fibres. As the concrete has to pass through a narrow outlet, coarse aggregates are not an option, and different rules apply when designing a sprayed concrete mix. For example, a higher content of fines, a maximum aggregates size, or the necessity of adding a hardening accelerator admixture.

Amount of rebound (fallout of concrete while spraying) is influenced by an appropriate concrete design, the sprayer device, as well as the skills of sprayer operator. The aim is to maintain concrete rebound as low as possible for material conservation, ecological and economical waste reduction. Rebound is in many cases washed off into nature and if the sprayed concrete contains fibres the polluting effect can be significant. In this aspect, polymer fibres are the worst, due to their long disintegration half-time.

Requirements set for sprayed concrete also differ from traditional concrete, where compressive strength is the essential property. The most important characteristic of fresh sprayed concrete is setting time, and flexure and bond strength after hardening.

2.1. Normative references

European standard EN 14487-1 (EN 2006) specifies properties testing and requirements on sprayed concrete and sprayed concrete with fibres, and European standard EN 14487-2 (EN 2007) is describing the execution of sprayed concrete. Individual tasks as a sampling of fresh and hardened concrete, testing of the compressive strength of young sprayed concrete and other important properties test methods are described in European standard EN 14488-1 to -7 (EN 2006).

Furthermore, there are standards concerning fibres for concrete which are referring either to steel or polymer fibres, namely EN 14889-1 (EN 2007) and EN 14889-2 (EN 2007). As our research is focused on the replacement of those two types of fibres by micro and macro basalt fibres, a combination of tests from both standards is applied. Both standards for steel and polymer fibres contain definitions, specifications and conformity, and are concluded by CE certification conditions. Test methods for fibres in concrete are specified by European standards EN 14845-1 (EN 2008) and EN 14845-2 (EN 2007). These standards contain reference concrete testing and its comparison to fibre reinforced concrete.

2.2. Fibres in concrete

Fibres in concrete were introduced especially to improve flexure strength and prevent drying shrinkage of fresh concrete. Dispersed fibre reinforcement is also considered as a replacement of traditionally used steel rebars in some cases. Fibres can vary in material, shape and dimension according to their purpose of use. The first fibres utilised as fibre reinforcement were steel fibres, followed by glass and synthetic fibres (Huang & Zhao 1995). Nowadays, under investigation are other material-based fibres like carbon, aramid or basalt, but due to their higher price resulting from small-scale automatized production or higher raw material cost, they are not yet widely used. Fibres can be straight or with performed ends for better anchorage in cement paste. One of the new type fibres are composite basalt fibres, where basalt micro-fibres are glued into strong element by epoxy resin. These composite fibres could be straight and with a rather smooth surface, or in a helical shape with rough surface to ensure a good bond between cement paste and fibre.

Table 1. Properties of fibres from various materials.

Type of fibres	Micro		Macro		
Supplier and name of the product	Krampe Harex PM12/18*	Basaltex BCS17-25.4-KV13*	Bekaert Dramix 3D 100/60 BG*	GCP Applied Technologies Strux 90/40*	Reforcetech MiniBar Gen3*
Material type [-]	Polypropylene	Basalt	Steel	Synthetic (PP, PE)	Basalt
Diameter [mm]	0,018 ± 10 %	0,017	0,62	eqv. 0,58 ± 5%	0,72
Length [mm]	12 ± 10 %	24,4	60	40 ± 5 %	30
Density [kg/m^3]	900	2.670	7.800	920	2.100
Melting point [°C]	170	1.350	1.510	160	1.350
Tensile strength [N/mm^2]	300	4.840	1.270	620	900
Young's modulus [N/mm^2]	1.550 ± 16 %	88.000 ± 5 %	200.000	9.500	44.000

*Technical sheets for fibres are listed in references in same order as fibres in table.

Another parameter of fibres for concrete is their cross-section, which can be circular or orthogonal. The orthogonal cross section is common for synthetic fibres. The dimensions of fibres are specified by length, diameter, equivalent diameter for orthogonal fibres and bi aspect ratio. According their size, fibres are classified as microfibres ($d < 0,3$ mm) and macrofibres ($d > 0,3$ mm). An overview of various types of fibres with their characteristics is presented in Table 1, as well as and photo documentation in Figure 2.

2.2.1. Basalt fibres

Currently, many research teams around the world are investigating the problematics of fibre reinforced concrete with various types of fibres, including basalt fibres (Singha 2012). Basalt fibres dispose by many beneficial mechanical and physical properties and it could be stated that they are more durable in aggressive conditions than glass fibres -and significantly cheaper than carbon fibres (Mohaghegh, Silfwerbrand & Arskog 2016).

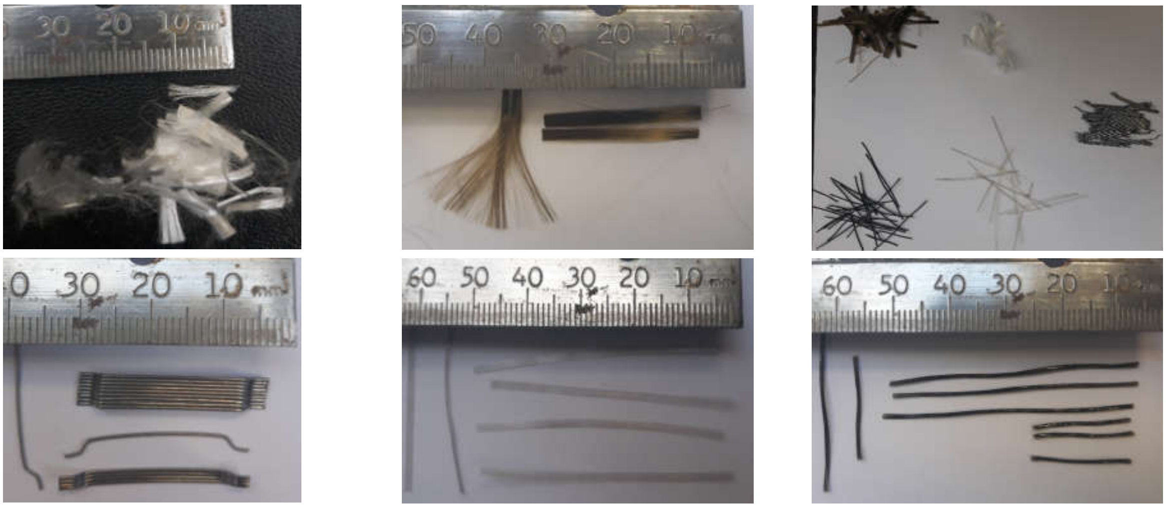

Figure 2. Examples of micro and macro fibres a) Krampe Harex PP-microfibers; b) Basaltex basalt microfibres; c) various types of micro and macro fibres, d) Dramix steel macrofibres, e) Strux synthetic macrofibres, f) Reforcetech basalt macrofibres

A study conducted by Vito NV (Boonen, Janssens & Manshoven 2017) was focused on a comparison of basalt and glass fibres and their energy efficiency differences during production. Results showed that basalt fibres have the same heat and electricity consumption, but there is an absence of processing emissions, usage of boric acid, waste and much lower required amount of epoxy resin for its composites. In total relevant contribution of 10 considered factors basalt fibres reached 80 % while glass fibres stated for 100 %. Also, resource depletion and water depletion are significantly higher in regard to glass fibres. The requirement of boric acid for glass production is one of the main drawbacks in its environmental profile.

Basalt rock has a lower melting temperature than iron ore or silica sand which are raw materials used for the production of fibres for dispersed concrete reinforcement. Polymer fibres do not require high melting temperature, but they are less environmentally friendly. Input materials used for the production of basalt fibres could be exclusively basalt rock, or a bland of basalt rock and other minerals. Production of a continuous filament is more sensitive than the production of rock wool and the chemical composition of input materials must be closely monitored, and therefore not every type of basalt rock is suitable.

Icelandic basalt is a young mineral, and its chemical composition is commonly more varying, which is not suitable for the presently used technologies for continuous filament production. Nevertheless, this might change due to innovations on used technologies for basalt continuous filament production and allowed less strict criteria for input raw material (Inman, Thorhallsson & Azrague 2016).

3. Experimental part

Experimental work consists of the evaluation of raw materials like cement, aggregates, additions and admixtures, and design of suitable sprayed concrete for laboratory conditions. Biggest emphasis were given to selection of aggregates, concerning maximum grain size and fines content, and hardening accelerating admixture.

Influence of various basalt fibre dose was verified by rheological properties testing on cement paste. A set of 4 mixes with 3 different basalt fibre doses were tested. Reference mix did not contain basalt fibres, and then the dose was gradually increased, to 4, 6 and 8 kg per 1 m^3 respectively. Those dosses are equal to 0,15, 0,22 and 0,3 vol.% (2 kg of PP-fibres is 0,22 vol.%). The rheological properties testing of fresh mortar was followed by casting prisms with dimension 40 × 40 × 160 mm. Properties of hardened cement mortar were tested after 24 hours according to European standard EN 196-1(EN 2016).

Same butches of basalt fibres were applied in sprayed concrete testing. Sprayed concrete without fibres was the reference mix and then mixes with 4, 6 and 8 kg of basalt fibres per 1 m^3 were prepared. Sprayed concrete was applied on a tilted board which was inclined by 20 degrees. Cement content, aggregate dose and amount of superplasticiser were kept constant, and the dose of water with accelerator slightly varied according to the addition of fibres. Shotcrete penetrometer from Mecmesin was used for measurements of early age strength, in the range of 0 to 1,2 MPa.

3.1. Mix design and components

For the selection of input materials and concrete design, mainly the Sika Sprayed Concrete Handbook (Sika, 2011) was used. Rapid cement from Aalborg, Denmark was used as the only powder component. It is convenient to consider the use of supplementary cementitious materials to reduce the cement dosage, which can vary between 380 to 500 kg/m^3. Within this testing, basalt fines were not added to omit more than one variable in mixes design and also because used aggregates had a high content of fines which contributed to compact mix. Two types of aggregates were tested. First aggregates used within this project were local Icelandic basalt aggregates, in fracture 0-8 mm. Unfortunately, due to lack of fines and a big share of particles of size 8 mm were exchanged for Norwegian aggregates in fracture 0-4 mm, which contained a greater amount of the fines (particles under 0,125 mm). Hardening accelerator admixture for faster hardening and plasticiser for obtaining more workable mix, the two most common admixtures in sprayed concrete, were used in various amounts according to the rising amount of basalt fibres. Basalt micro fibres BCS17-25.4-KV13 from Basaltex were used (Basaltex) in dose 0, 4, 6 and 8 kg per 1 m^3.

The design of sprayed concrete was inspired by conventionally used sprayed concrete mix designs, but converted to a laboratory scale. The laboratory sprayer supplied by Fishstone GFRC can spray concrete with maximum particle 8 mm and as the concrete mix is moved only by its weight towards the sprayed outlet more viscose mix is required to omit blocking of the outlet. The presence of basalt fibres has not caused any blocking of the nozzle while spraying and rather helped to avoid segregation of the mix.

3.2. Cement mortar with basalt fibre testing

Testing of mortar with various basalt fibre content was prepared from standard sand EN 169-1, cement, water, plasticiser and optionally with air reducing admixture. The volume of the testing batch 1 l was maintained by lowering aggregates dose by weight according to the dose of basalt fibres. Device Viscometer 6 from ConTec was used for the evaluation of the rheological properties of the fresh mortar with varying content of basalt fibres. Mortar mix design was kept as it is commonly used in a laboratory at Innovation center of Iceland, to obtain comparable results to other projects. Rheological properties were recorded at 8, 15 and 18 min from the beginning of mixing. After the last measurement was taken, the density of fresh mortar was measured, and test samples were cast for strength properties evaluation at the age of 24 hours. Presence of fibres in combination with the mixing procedure resulted in higher air content in the mortars, and therefore air reducing admixture was used to maintain air content at approximately the same level in all mixes. Results of rheological properties testing are presented in Figure 3 and properties of the hardened mortar in Table 2 and Figure 4.

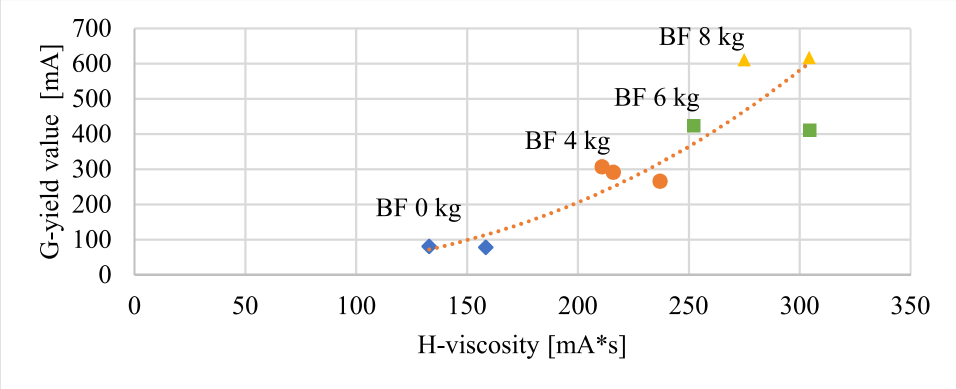

Figure 3. Rheological properties of cement mortar with various basalt fibre dose.

A higher content of basalt fibres reduces plastic viscosity gradually. Rheological parameters G-yield value equal to yield value τ and H-viscosity equal to plastic viscosity μ are obtained by use of ConTec Viscometer 6 (Kubens 2010). As the water and superplasticiser doses were kept constant and the surface of particles which needed to be covered by cement paste increased, mortar became stiffer. From the results of fresh mortar density could be concluded, that air content was kept constant by an increase of defoamer admixture dose along increasing basalt fibre dose.

Table 2. Properties of hardened cement past with various dose of basalt fibres after 24 hours ageing.

	Compressive strength [N/mm^2]	Flexure strength [N/mm^2]	Density fresh [kg/m^3]	Density hardened [kg/m^3]
BF 0 kg	26,6	5,78	2355	2255
BF 4 kg	28,1	6,00	2362	2275
BF 6 kg	29,4	5,97	2351	2258
BF 8 kg	27,2	5,27	2341	2203

Strength properties of hardened mortar varied by 2,8 N/mm^2 which is not significant strength improvement by addition of basalt fibres. Flexure strength was slightly higher in case of mix BF 4 kg and BF 6 kg. Mortar mix with 4 kg of basalt fibres seems to be most beneficial as the rheological properties are still sufficient and strength properties very good. The dose of 8 kg (0,3 vol.%) is too high, and fibres are nor evenly dispersed or do not bond properly in cement paste. Bond properties could improove through time, but this might be subject for further research.

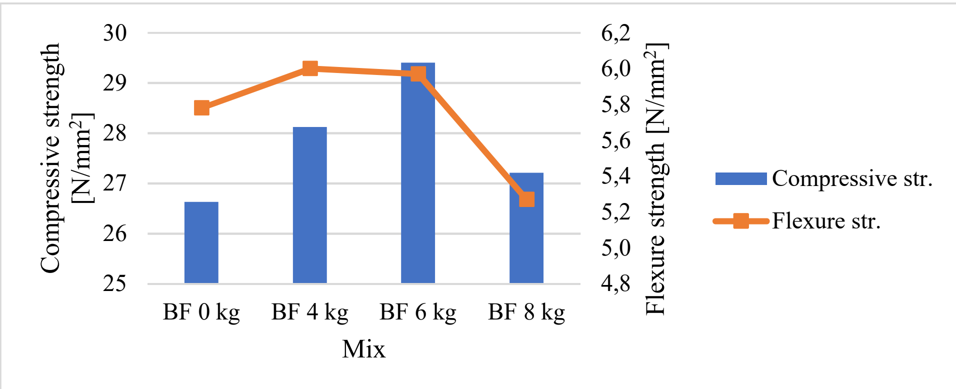

Figure 4. Graphical interpretation of hardened cement mortar properties 24 hours after casting.

3.3. Sprayed concrete with basalt fibres testing

Sprayed concrete was designed with a standard aggregate in fracture 0-4 mm and a cement dose 400 kg/m^3. Amount of water, plasticiser and accelerator varied according to the dose of basalt fibres, which were 0 kg in the case of the reference mix, and then gradually increased to 4, 6 and 8 kg/m^3. During the sprayed concrete mixing no sign of excessive air content in mixes was recorded. Early age strength of sprayed concrete was tested by penetrometer according to the European standard EN 14488-2 method A (EN 2007).

Figure 5. Photo documentation of the surface of test samples with various basalt fibres dose: a) 0 kg, b) 4 kg, c) 6 kg, d) 8 kg.

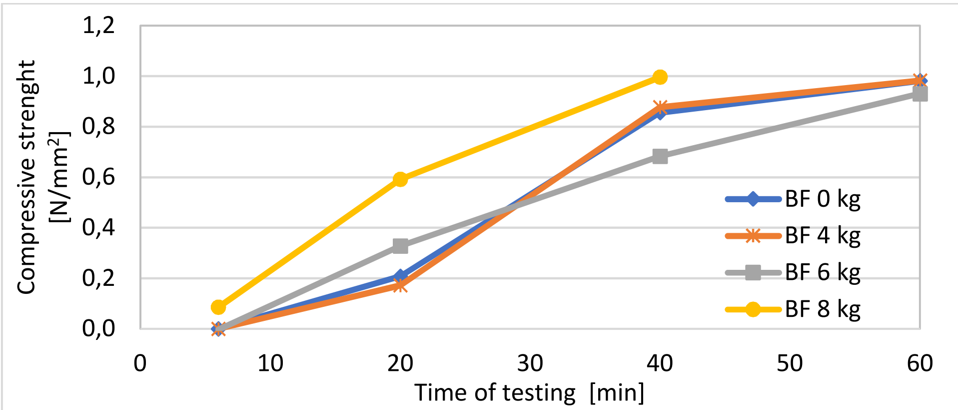

Figure 6. Comparison of early age compressive strength gain of sprayed concrete with 0, 4, 6 and 8 kg of basalt fibres per cubic meter tested by penetrometer.

All prepared mixes prove satisfying behaviour in the fresh state and also during the early phase of ageing. The consistency of fresh sprayed concrete was getting more compact and slightly stiffer with increasing dose of basalt fibres. To omit difficulties with spraying, slightly higher water content and accelerator doses were used. Testing of early age compressive strength (according to EN 14488-2 Method A (EN 2007)) was performed 6, 20, 40 and 60 minutes from spraying termination. The sample with 8 kg of basalt fibres was not measurable at 60 min because the strength exceeded the measurable range of penetrometer. Small fibre agglomerations were visible in the sample with 6 kg of basalt fibres, most probably caused by imperfect mixing procedure. Agglomeration of fibres occurred only in case of mix with 6 kg dose and no trend of rising fibre agglomeration along with dose increase was observed. Furthermore there was performed fibre reinforced concrete testing and no agglomeration of fibres was observed either. Results of fibre reinforced concrete are not subject of this article and not going to be further discussed. Early strength classification of young sprayed concrete is part of the European standard EN 14487-1 (EN 2006) and was used for evaluation of our tested mixes. All mixes were classed as J1, 10 minutes time from termination of mixing; after 20 minutes from zero time, mix BF 8 kg and BF 6 kg were already classified as J2. 30 minutes from the termination of mixing, all mixes belonged to class J2.

Conclusion

Testing within this study was focused on the influence of basalt fibres on the rheological properties of fresh mortar and its strength characteristics after 24 hours of ageing. Results validated our assumption that basalt fibres are going to reduce the viscosity and workability of fresh mortar. Based on results from flexure and compressive strength testing after 24 hours, it can be stated that 4 kg of basalt fibres could be the optimal dose. This dose is convenient not only for ecological and economic reasons, but also due to sufficient performance in the fresh state.

The second part of the study deals with sprayed concrete design and its testing in laboratory conditions. Some changes had to be done to conventional mix designs for field sprayed concrete, like the maximum aggregate grain size was reduced to 4 mm and basalt fibres doses of 0, 4, 6, 8 kg/m^3 which required a slight increase of water and accelerator content. Measurements of early age strength by penetrometer were performed 6, 20, 40 and 60 minutes after termination of spraying. Samples with basalt fibres were more compact and performed better in the sense of uniform layer depth and lower segregation. It could be stated that early age strength is gained faster with a higher dose of basalt fibres. All tested samples at the time of 30 minutes from the termination of spraying were classified as J2 according to EN 14487-1 (EN 2006).

Acknowledgements

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