GREENBAS

**Sustainable Fibres
from Basalt Mining**

**Nordic Council
of Ministers**

GREENBAS

Sustainable Fibres from Basalt Mining

Birgir Johannesson, Thorsteinn Ingi Sigfusson, Hjalti Franzson, Ögmundur Erlendsson, Björn S. Harðarson, Eythor Rafn Thorhallsson, Arni B. Arnason, Kamal Azrague, Marianne Rose Kjendseth Wiik, Sirje Vares, Anna Kronlöf, Pertti Koskinen, Tapio Vehmas

GREENBAS

Sustainable Fibres from Basalt Mining

Birgir Johannesson, Thorsteinn Ingi Sigfusson, Hjalti Franzson, Ögmundur Erlendsson, Björn S. Harðarson, Eythor Rafn Thorhallsson, Arni B. Arnason, Kamal Azrague, Marianne Rose Kjendseth Wiik, Sirje Vares, Anna Kronlöf, Pertti Koskinen, Tapio Vehmas

ISBN 978-92-893-4808-9 (PRINT)

ISBN 978-92-893-4809-6 (PDF)

ISBN 978-92-893-4810-2 (EPUB)

<http://dx.doi.org/10.6027/TN2016-564>

TemaNord 2016:564

ISSN 0908-6692

Standard: PDF/UA-1

ISO 14289-1

© Nordic Council of Ministers 2016

Layout: NMR

Cover photo: Fjalar Sigurðarson

Print: Rosendahls-Schultz Grafisk

Copies: 250

Printed in Denmark

Although the Nordic Council of Ministers funded this publication, the contents do not necessarily reflect its views, policies or recommendations.

Nordic co-operation

Nordic co-operation is one of the world's most extensive forms of regional collaboration, involving Denmark, Finland, Iceland, Norway, Sweden, the Faroe Islands, Greenland, and Åland.

Nordic co-operation has firm traditions in politics, the economy, and culture. It plays an important role in European and international collaboration, and aims at creating a strong Nordic community in a strong Europe.

Nordic co-operation seeks to safeguard Nordic and regional interests and principles in the global community. Shared Nordic values help the region solidify its position as one of the world's most innovative and competitive.

Contents

Foreword.....	5
Summary	7
Sustainable fibres from basalt mining	7
Final Report.....	8
Introduction	9
Objectives	11
1. Innovation Center Iceland – ICI.....	13
1.1 Defining selection criteria for continuous Basalt Fibres.....	13
1.2 Chemical composition.....	13
1.3 Acidity Modulus – Ma.....	14
1.4 Viscosity modulus	16
1.5 Basalt selection process	17
1.6 The search for basalt in Iceland	18
1.7 Viscosity measurements	24
1.8 Contact with Lipex.....	25
1.9 Business model for a Continuous Basalt Fibre Plant.....	26
1.10 Magnetic separation	27
1.11 Conclusions	29
1.12 References.....	29
2. Iceland Geosurvey – ISOR.....	31
2.1 Geological setting	31
2.2 Sampling criteria.....	31
2.3 References.....	41
3. Reykjavik University – RU	43
3.1 Tasks done by Reykjavik University members	43
4. JEl	47
4.1 Collection of Samples	47
4.2 Basalt Fibre Manufacturing	47
4.3 Basalt Fibre Market	48
4.4 Columnar Basalt	49
4.5 International cooperation.....	50
5. SINTEF	51
5.1 Objectives.....	51
5.2 Continuous basalt fibre (CBF) production	51
5.3 Materials and methods	52
5.4 Results.....	53
5.5 References.....	55

6.	VTT.....	57
6.1	Objectives	57
6.2	Tasks.....	57
6.3	Main results.....	58
6.4	Conclusions	65
6.5	Information on the importance of the project for the sustainable raw materials sector	66
6.6	Dissemination	67
6.7	Information on the societal implications of the project.....	68
6.8	Information on the importance of the project results to the Nordic region	68
6.9	References	68
7.	Dissemination of results	69
7.1	Innovation Center Iceland	69
7.2	Reykjavik University	69
8.	GREENBAS General Conclusions.....	73
8.1	Work Package 1. Mining and production	73
8.2	Work Package 2. Sustainable use of energy and resources	73
8.3	Work Package 3. Life Cycle Analysis and sources of raw materials	74
8.4	Work Package 4. Production of basalt fibre bars – Choice of mines for concrete products.....	74
8.5	Work Package 5. CBF as green reinforcement in polyester resin	74
	Sammendrag	75

Foreword

Among the Nordic countries, Iceland is clearly the volcanic one. This affects the status of mining in the country but, on the other hand, leads to vast amounts of resources related to volcanism.

The background of the GREENBAS project is rooted in my work for the rockwool manufacturer Steinull hf in the town of Saudarkrokur in North-Western Iceland in the beginning of the 1990's. The factory was and is using coastal basalt sand as a resource and an electrical process to produce basalt rockwool which is used for insulation both domestically as well as for export.

A production with more added value would involve continuous basalt fibres rather than the discontinuous material. It was clear, however, that this type of product requires different raw materials and it was not obvious that it could be mined from Icelandic raw materials.

The well-known materials hitherto used for producing continuous basalt fibres in the world are from Eurasian and continental mines.

Thus, it was clear from the beginning that a considerable effort would be needed in order to adjust the manufacturing process to the geologically unique conditions in Iceland.

The opportunity to perform the research required was opened by the support of the newly established NordMin programme.

It was clear to us that joining forces with our related institutions in the Nordic countries, we seemed to be able to come to important conclusions about the viability of such an undertaking.

It turned out that such collaboration was possible and that our Nordic partners were able to contribute with crucial elements of a project.

The following report is a manifesto of the success of this partnership.

Thorsteinn I. Sigfusson

Summary

The GREENBAS project is about the feasibility of producing continuous basalt fibres from Icelandic basalt. The project was made possible with support from NordMin, with the aim to develop the Nordic mining and mineral industry.

Geological investigations by Iceland Geosurvey have resulted in insight into locations of the most ideal materials. Work at Innovation Centre Iceland (ICI) led to the definition of the basalt properties required. ICI also analysed the business conditions for a start-up factory. The involvement of JEI has ensured industrial relevance in tandem with the contribution of the University of Reykjavik team in gaining an understanding of the importance of applications in building materials.

The involvement of SINTEF Norway and VTT Finland was crucial. They provided their expertise to analyse the life-cycle of basalt fibres and the feasibility and need of artificial external components.

On basis of this project, a new phase can be started: the preparations for establishing a continuous basal fibre factory in Iceland.

Sustainable fibres from basalt mining

- NordMin Grant Agreement no.: 14814102.
- Project duration: 1 April, 2014–30 September, 2016.
- Coordinator: Innovation Center Iceland.

Final Report

Participants

- Innovation Center Iceland – ICI Iceland. Birgir Johannesson and Thorsteinn Ingi Sigfusson.
- Iceland Geosurvey – ISOR Iceland. Hjalti Franzson, Ögmundur Erlendsson and Björn S. Harðarson.
- Reykjavik University – RU Iceland. Eythor Rafn Thorhallsson.
- JEI ehf (Íslenskur Jarðefnaiðnaður) Iceland. Arni B. Arnason.
- SINTEF Norway. Kamal Azrague and Marianne Rose Kjendseth Wiik.
- VTT Finland. Sirje Vares, Anna Kronlöf, Pertti Koskinen, Tapio Vehmas.

Introduction

This work was conducted as a part of the “Sustainable Fibres from Basalt Mining” (GREENBAS) project, funded by NordMin – A Nordic Network of Expertise for a Sustainable Mining and Mineral Industry.

Apart from obtaining materials for roadwork, very little mining has been done in Iceland. With the possible mining of special basalt for the production of continuous basalt fibres, a new mining tradition could take hold in the country. An industry connecting the mining of basalt and linking it to rather high value extracted fibres could be established. This, in turn, would result in the formation of a new sector within Icelandic energy, bringing us closer to the Nordic tradition and requiring new skills from the population involved in this type of manufacturing.

The societal implications could be significant, mainly in the public’s conception of the traditional “output of volcanism” in the country. Furthermore, it is clear that the significant modern demand for consideration of any potential impact on the environment would be very important to such a transition.

Implications for the Nordic region are also an important part of this work. In the project, the Icelandic team has shared knowledge from experience in the Nordic countries where aspects of mining – such as life cycle analysis of the products from birth to end of life – have been used to identify the very green components in production of Icelandic basalt fibres. The production of basalt fibres in Iceland would mark its entrance into the union of countries engaged in mining exploration in the Nordics.

A sustainable raw materials sector has also come out of this project. At the moment, Iceland’s perhaps most sustainable raw material product is water. It manifests its importance in consumption, as a hydroelectric foundation, and in agriculture. Materials produced in Iceland from mined elements are almost solely found in the infrastructure of buildings, roads and bridges as well as harbours.

As stated earlier the use of mined basalt in the production of continuous fibres would constitute a new element in the production of sustainable raw materials for industry. The GREENBAS project has aimed to find a unique material with respect to sustainability.

Keeping all the above points deep in mind, a Nordic group of experts have worked together in the NordMin project called GREENBAS. The main question has been: is it possible to utilize basalt in Iceland to establish state-of-the art continuous basalt fibre

production based on renewable energy and with the smallest possible carbon footprint, with a life cycle that would be unique to the world.

The Nordic team has succeeded in this goal. Geological investigations by Icelandic Geosurvey (*ISOR*) have led to new insights into where to search for the most ideal materials. Research by *Innovation Centre Iceland (ICI)* resulted in finding a definition of the conditions for the chemical composition of the mined ore following probing of 154 areas in Iceland. *ICI* also analysed the business conditions for a start-up factory in Iceland. The involvement of the mining company *JEI* in Iceland has ensured industrial relevance in tandem with the contribution of the *University of Reykjavik* team in gaining an understanding of the importance of continuous fibres in various building materials in Iceland.

The involvement of experts from *SINTEF* Norway and *VTT* Finland was crucial to this work. They provided their expertise to analyse the life-cycle of basalt for production, its demand, and the feasibility of artificial external components.

It is now feasible, on basis of this project, to begin a new phase: the preparations for establishing a continuous volcanic basalt factory in Iceland.

In retrospect it can be said that the Nordic team reached a very important goal during this project. Without the vital financial and managerial assistance provided by NordMin, this goal would not have been reached.

Professor Thorsteinn I. Sigfusson

University of Iceland and Innovation Center Iceland.

Objectives

The objectives of the GREENBAS project were:

- To gain knowledge and expertise on relevant properties of basalt required to produce high quality continuous basalt fibres (CBF). This involves knowledge about experimental facilities and modelling.
- To search for basalt in Iceland suitable for production of CBF.
- To map the location of analysed basalt samples in Iceland with information about the petrology of the materials.
- To shed light on the applicability of CBF for concrete and asphalt, both locally and in the Nordic countries. This requires modelling and testing of the compatibility of the materials for concrete and asphalt.
- To make a life cycle analysis of CBF with the aim of comparing production using renewable hydro-electric power, versus production using gas or oil-based energy resources. It is expected that a significant carbon footprint reduction can be achieved. Analysis of resource efficiency will be included.
- To estimate how additional sources of oxides can be used to modify the composition of basalt. This includes investigation into possible oxide sources and how they can be added to selected basalt samples. The aim of the modification is to make the basalt ideally suitable for fibre production.
- To estimate the waste from a basalt fibre plant in Iceland and how it can be managed.
- To set up a plan for mining and production of continuous basalt fibres in Iceland.

A description of the contribution of all partners now follows.

1. Innovation Center Iceland – ICI

Birgir Jóhannesson and Thorsteinn Ingi Sigfússon

1.1 Defining selection criteria for continuous Basalt Fibres

The chemical composition and mineral content of basalt varies considerably. For applications such as tiles, stone castings or staple fibres, basalt with a wide range of properties can be used. However, for production of continuous basalt fibres (CBF), the requirements become much more stringent and only a narrow range of compositions can be used to make CBF [1–3]. With these strong requirements for composition and mineral content, the list of possible basalt mines in the world becomes very short [1, 3]. Today, major manufacturers of CBF are known to use raw material from mines in western Ukraine or Georgia, consisting of andesitic basalts with SiO₂ content more than 50wt% [4, 5].

In the search for possible basalt mines in Iceland, a method with a set of criteria has to be defined that can be applied in selecting basalt suitable for production of CBF. The first step in the selection process is to measure the oxide content.

1.2 Chemical composition

The chemical composition and mineralogical features of basalt (petrology) define its ability to form fibres and these properties therefore have to match certain criteria. Limits for oxide content from four sources are shown in Table 1. Column A shows limits given by Boris Gromkov and Natalya Demina at Stekloplastik during a visit to ICI in June 2014 [6]. Column B shows limits given by Lipex GmbH in Germany [7]. Column C shows limits from the web site www.bavoma.com [8]. Column C shows wider limits by ref. [9], applicable to products like e.g. slag wool and stone castings.

Table 1: Limits for chemical composition of basalt for CBF production.

Oxide	A – Ref. [6]	B – Ref. [7]	C – Ref. [8]	D – Ref. [9]
SiO ₂	50–54% (48–56%)	45–60%	47.5–55.0%	38–55%
Al ₂ O ₃	7.5–15%	12–19%	14.0–20.0%	3–20%
FeO–Fe ₂ O ₃	7.0–15% (18%)	5–15%	7.0–13.5%	2–18%
MgO	3.0–7.0%	3–7%	3.0–8.5%	1–24%
TiO ₂	0.1–2.0%	0.1–2%	0.2–2.0%	
NaO+K ₂ O+CaO	0.1–18%		2.5–7.5% (Na+K)	
CaO		6–12%	7.0–11.0%	17%
MnO			< 0.25%	0.3%
SO ₃			< 0.2%	

Figure 1 graphically displays the limits in Table 1. The limits by Kochergin *et al.* [9] are obviously much wider than the others and apply to broader applications, including slag wool. These limits are therefore not relevant for production of CBF. The limits by Stekloplastik, Lipex and Bavoma.com [6–8] apply to the production of quality CBF and are much narrower. The limits for Al₂O₃ from Stekloplastik are surprisingly different from the others.

1.3 Acidity Modulus – Ma

An important parameter calculated from the oxide content is the acidity modulus (Ma), defined by [e.g. 10, 11, 5]:

$$M_a = \frac{SiO_2 + Al_2O_3}{CaO + MgO}$$

Signs for oxides denote weight % of oxides. M_a denotes the ratio of acidic to basic oxides. Values quoted in the literature for M_a for different production forms are given in Table 2.

If M_a < 1.2, the fibre is called slag wool. They are very brittle and show a poor chemical resistance (e.g. [1, 9]). If M_a = 1.2–1.5, the fibre is considered to be a mineral wool. These fibres are brittle but have acceptable insulation properties. If M_a > 1.5, the fibre is called rock wool or basalt fibre e.g. [1]. Another classification is based on the SiO₂ content. Basalt rock is considered alkaline if SiO₂ is lower than 42%, mildly acidic if it is 43–46% and acidic if over 46% [12].

The optimal chemical composition for production of continuous basalt fibres is considered to be one that gives an acidity modulus in the range 3–6 [10].

Figure 1: Limits in wt% for four oxides. Limits from Stekloplastik, Lipex and Bavoma [6–8] are for CBF production. Limits from Kochergin *et al.* [9] are for production of short fibres

Table 2: Classification of acidity modulus.

Reference	Acidity modulus, Ma
[9]	0.8–1.3 Slag
[1]	< 1.2 Slag wool 1.2–1.5 Mineral wool > 1.5 Rock wool, basalt fibre
[13]	< 1.8 Mineral wool > 1.8 Rock wool, basalt fibre
[10]	> 1.2 staple and continuous fibre Optimal for CBF

1.4 Viscosity modulus

The viscosity modulus M_v is defined by [e.g. 5, 13–15]:

$$M_v = \frac{x_{SiO_2} + x_{Al_2O_3}}{2x_{Fe_2O_3} + x_{FeO} + x_{CaO} + x_{MgO} + x_{K_2O} + x_{Na_2O}}$$

x is the molar fraction of oxides. The limits given for M_v for CBF production are 2.3–2.7 by bavoma.com [8] and 2–3 by Lipex [7].

1.4.1 Viscosity

In the production of basalt fibres, basalt has to be heated and melted in the fibre production process. One of the most important properties of basalt that determines its suitability for manufacturing continuous fibres is the viscosity, η (units of Pas). The viscosity has to be within a certain range to allow for the optimum production of fibres. The viscosity of basalt melt, $\eta(T)$, can be calculated using a simple equation which has been determined empirically [11]. The variables in the equation are composition in weight %, temperature, T , and the acidity modulus, M_a :

$$\eta(T) = 3.62 \frac{(SiO_2)^{3.07} (FeO + Fe_2O_3)^{1.34}}{(Al_2O_3)^{0.16} (CaO)^{0.40} (T - 1100^\circ C)^{2.58}} (M_a)^{1.25}$$

T is temperature in $^\circ C$. This equation is set up for one particular type of basalt and a specific temperature interval. The equation is therefore only applicable to basalt that has the same or a similar composition and is in the temperature interval 1200–1450 $^\circ C$ [11]. The composition of the basalt is given in Table 3.

Table 3: Composition of basalt used in the equation for viscosity

Oxide	Wt%
SiO ₂	60.60
Al ₂ O ₃	18.20
TiO ₂	0.95
MnO	0.048
FeO+Fe ₂ O ₃	7.20
MgO	2.20
Na ₂ O	2.30
K ₂ O	3.45
P ₂ O ₅	0.18
Other	4.70

Other ways to calculate viscosity of basalt melts are available on the internet for free. These include the programs Magma, Comagmat and a program developed by the authors of reference [18].

Silica SiO_2 , alumina Al_2O_3 , magnesium oxide MgO and trivalent iron Fe_2O_3 are oxides that increase viscosity. Alkali metal oxides K_2O and Na_2O and divalent iron FeO lower viscosity. The effect of other oxides, including CaO , is complex and not unique [11].

Basaltic melts are capable of forming continuous fibres in a certain (working) viscosity range that is 10–30 Pas [11, 16, 17]. This result is based on experimental data. Such a range of viscosity is typically within a range 1350–1400°C for basalt used for production of continuous fibres [16].

1.4.2 Surface tension

According to reference [13], the surface tension σ of molten basalt is important. In particular, it is stated that: “The operating temperature is determined by the ratio of viscosity to surface tension (η/σ). This parameter is also called fibreizability in the technology of continuous silicate fibres. The greater the η/σ ratio is, the more stable the process is” [13]. According to [16], the lower limit of the working viscosity range of a melt is characterized by a certain viscosity-to-surface tension ratio. For most molten aluminosilicate glasses, from which high modulus fibres are drawn, the ratio η/σ is less than 100 Pas/(N/m) [16].

According to bavoma.com [8], the surface tension of basalt suitable for fibre production is 350–410 mN/m at 1450°C and 400–500 mN/m at 1300°C. If the viscosity is 10–30 Pas, then the ratio η/σ is 29–86 respectively.

1.5 Basalt selection process

Based on the literature review and discussions with scientists in the field, the following steps should be taken in the process of selecting basalt for production of CBF:

- Visual inspection. The rock should be homogeneous, without obvious inclusions.
- Measure chemical composition. See Table 1.
- Evaluate acidity modulus (Ma) and viscosity modulus (Mv). The acidity modulus should be in the interval 3–6 and the viscosity modulus in the interval 2–3.

- For selected samples, measure viscosity, melting temperatures, electrical resistivity, crystallisation and other relevant properties (e.g. loss of ignition, degassing, etc.).
- Final selection

In addition to this, several other factors have to be taken into account. Ideally the location is in an already existing mine. If the location is not a mining site, it must be possible to access it by roads and the location must not be sensitive (e.g. not in a national park).

1.6 The search for basalt in Iceland

Samples were collected from 154 locations during four summers from 2013 to 2016. The batch labels and specimen numbers are shown in Table 4. The chemical composition of all samples has been measured and the acidity and viscosity moduli calculated for each sample. Column charts were made for each sample batch and examples of these are shown in Figure 2.

Table 4: Samples collected in the GREENBAS project

Batch	Year collected	Number of samples
South I	2013	21
BTR	2014	14
HR-JEI	2014	10
ERP	2015	12
HF	2015	87
HF-BJ	2016	4
HF-ERP	2016	6
	Total	154

Figure 2 shows examples of results for the SiO₂ content of samples collected in the project. A general feature is that SiO₂ is close to the lower limit, or in the interval 45–50wt%. Exceptions are to be found for a few samples in the South I and BTR batches. The next step in the selection process is to calculate the acidity and viscosity moduli. The results for the South I, BTR and HF 2015 batches are shown in Figure 3.

Figure 2: Four column charts of SiO₂ for samples in batches South I, BTR and HF 2015, showing upper and lower limits. The red column on the right is the reference sample from Ukraine, known to be used for production of CBF. The red, horizontal line shows the value of SiO₂ content in this reference sample

Figure 3: Six column charts showing Acidity modulus and Viscosity modulus for the South I, BTR and part of HF 2015 batches. The red column furthest to the right represents the reference sample from Ukraine. The dark blue column in the South I batch is a sample from the Holuhraun eruption 2015

Figure 3 shows that for virtually all samples in the HF 2015 batch, the acidity modulus is near the lower limit and the viscosity modulus is below the lower limit. None of these samples therefore pass the test. A few samples in the South I and BTR batches seem to be either within or near to being within the limits. It must be noted that although a given sample is either close or within limits for a given property, the sample has to be within limits on all parameters. This means that a sample can fail to pass the test by containing e.g. excessive TiO_2 content, as an example.

A thorough examination of every parameter for all of the 154 samples collected in the project resulted in three samples being selected for further experimental analysis. These samples are from the following locations:

- Næfurholt – Hekla eruption 1845 (same location as South I–7).
- Skjólkvíar – Hekla eruption 1970.
- BTR 13 – Borgarfjörður.

These samples can all be classified as being andesite, with a SiO₂ content of more than 50%. The chemical composition of the samples is shown in Table 5.

Table 5: Oxide content of the three samples selected for further analysis

Oxide	BTR-13 Borgarfjörur Weight %	Næfurholt Hekla 1845 Weight %	Skjólkvíar Hekla 1970 Weight %
SiO ₂	56.7	54.1	54.1
TiO ₂	1.78	1.93	2.07
Al ₂ O ₃	13.0	14.7	14.5
FeO	9.08	11.5	10.9
Fe ₂ O ₃	4.08	1.06	1.06
CaO	5.82	6.83	6.61
MgO	1.98	2.79	2.94
Na ₂ O	4.04	4.07	4.03
K ₂ O	1.20	1.26	1.23
Sum	97.7	97.7	97.5

These three samples were sent to Lipex in Germany on 8 July, 2016 for analysis of their suitability for basalt fibre production, including measurement of chemical composition. On 11 August a report was received on the work Lipex did on the samples. The conclusion was that all three samples required the addition of CaO or MgO to reduce the acidity modulus. They recommended the addition of burnt lime, which mostly consists of CaO. After the addition of 5% burnt lime, the acidity modulus was within the limits required. The CaO content of the samples before and after the addition of burnt lime is shown in Figure 4. Figures 5 and 6 show the acidity (Ma) and viscosity (Mv) moduli before and after the addition of burnt lime. For the three specimens with the modified composition, the acidity modulus is well within the limits and the viscosity modulus near the lower limits. In all cases the material seems to be suitable for fibre production.

This shows that a simple addition of one material – burnt lime in this instance – is sufficient to make the basalt suitable for production of CBF.

Figure 4: CaO content of the samples measured by Lipex, BTR-13 (column 3), Hekla eruption 1845 (4) and Hekla eruption 1970 (5) before addition of burnt lime (CaO). Columns 6, 7 and 8 show CaO content of these samples after addition of 5wt% burnt lime. Column 1 shows CaO content in the reference sample from Ukraine

Figure 5: Acidity (Ma) moduli for the samples measured by Lipex: BTR-13 (column 3), Hekla eruption of 1845 (4) and Hekla eruption 1970 (5). Columns 6, 7 and 8 show Ma and Mv after the addition of burnt lime (CaO). The red column furthest to the left represents the reference sample from Ukraine

Figure 6: Viscosity (Mv) moduli for the samples measured by Lipex: BTR-13 (column 3), Hekla eruption of 1845 (4) and Hekla eruption 1970 (5). Columns 6, 7 and 8 show Ma and Mv after the addition of burnt lime (CaO). The red column furthest to the left represents the reference sample from Ukraine

To fully evaluate the suitability of a sample for fibre production, the viscosity, electrical resistivity and solidification behaviour (e.g. liquidus and solidus temperatures) have to be measured. After some discussion, it was decided that Lipex would measure the viscosity of one modified specimen (BTR-13 with added burnt lime) to obtain information about the melting temperature and also fibre drawing temperature. It was also decided that Lipex would measure the electrical resistance curves and crystallisation behaviour of all three samples in order to find out if electrical heating is applicable as well as to estimate the “drawability” of the material. If there is any crystallisation inside the fibres, it will affect the tensile modulus and other mechanical properties. The results from these measurements are expected in November/December 2016.

The general conclusion of this work is that the three samples selected for further analysis, the sample from Borgarfjörður (BTR-13) and the two samples from Hekla (Næfurholt 1845 and Skjólkvíar 1970) are all suitable for CBF production after the addition of burnt lime (CaO).

1.7 Viscosity measurements

Anton Paar in Austria manufactures many types of equipment, including equipment for viscosity measurements of rock samples. Contact has been established with Anton Paar and they volunteered to measure the viscosity of four specimens of Icelandic basalt [19]. These measurements have been performed and reported to us. Two of the samples turned out to be uninteresting for any further consideration. The other two are the samples South I-7 and BTR-13. The South I-7 sample is from a lava field at Næfurholt, from the Hekla eruption 1845. The BTR-13 sample is from Borgarfjörður. Material from both of these locations was sent to Lipex for further analysis (see previous section).

Figures 7 and 8 show viscosity measurements for the South I-7 and BTR-13 samples, displaying three curves on each graph. The measured curves are shown with circles. The curves with triangles are based on calculations by the program Magma. The curves with squares are based on calculations from a program developed by reference [18]. The horizontal lines at 10 and 30 Pas show the limits within which the viscosity of basalt must lie during fibre drawing. The vertical lines show the temperature interval Stekloplastic uses in drawing of fibres.

Figures 7 and 8 show that the calculations according to the program in reference [18] correspond well with the measured viscosity. The H₂O content of the material is an adjustable parameter in the model.

The important conclusion to take away is that the measured viscosity curves for both these samples show that the samples seem to be applicable for fibre drawing. In the temperature interval between 1380 and 1400°C, the viscosity lies within the required limits of 10–30 Pas.

Both of these samples, BTR-13 and South I-7 have been selected for further analysis (The South I-7 sample is from the same location as the Hekla eruption 1845 – Næfurholt). Viscosity, electrical resistivity and crystallisation behaviour are being measured by Lipex to ascertain the suitability of the material for fibre drawing.

All three samples that have been selected for further analysis are classified as *andesite*. The reference sample from Ukraine is also *andesite*. One of the conclusions of this project is that further exploration of the suitability of mines in Iceland for production of CBF should focus on basalt of the *andesite* type, with more than 50 wt% SiO₂.

Figure 7: Viscosity measurement of the South I-7 sample (Hekla eruption 1845 – Næfurholt)

Figure 8: Viscosity measurement of sample BTR-13 (Borgarfjörður)

1.8 Contact with Lipex

Lipex Corporation is a prominent producer of equipment for the production of glass and basalt fibres. They are located in Puchheim, near Munich, Germany. On 22 June, 2015, Thorsteinn Ingi Sigfusson had a meeting with Gert Lichtblau and Toni Schneider at the Lipex headquarters. Several issues regarding production of basalt fibres were discussed, including the estimated cost of setting up a plant producing 50 tons per year of continuous basalt fibres. Lipex has experimental facilities to measure the properties of

glass and basalt. It was discussed that Lipex would be willing, at a certain cost, to experimentally evaluate the suitability of Icelandic basalt for fibre production. Four samples were sent to Lipex in July 2016. It was then decided to measure viscosity of one sample and do selected experiments on other two.

1.9 Business model for a Continuous Basalt Fibre Plant

A rudimentary business model has been set up in Excel for a plant producing continuous basalt fibres in Iceland. This model is excellent in the sense that it gives results for a given set of input values. How well the model represents operation of an actual plant therefore depends on how reliable and accurate the input parameters are.

The most important input parameters in the model are given in Table 6.

Table 6: Input parameters in the CBF plant model.

Parameter	Value
Buildings	EUR 500,000
Equipment	EUR 1,500,000
Cars	EUR 30,000
Stock	EUR 1,000,000
Loan (15 years)	EUR 1,030,000
Salary/year (5 persons)	EUR 256,000
Price/kg CBF	EUR 2–15
Annual production CBF	50 tons
Cost of mining, transport and grinding basalt	EUR 47,000

It is known that Russian providers sell basalt fibres at EUR 2–3/kg. The market for high quality basalt fibres is estimated to be 10 kt/year. The price for high quality basalt fibres is in the range of EUR 10–15/kg.

Table 7 shows results of the business model for three values of the sensitivity factor, showing how well plans match with reality. For example, a sensitivity factor of 0.7 says that 70% of the plans have materialised. This can apply to both quantity and price. The three values of the sensitivity factor in Table 7 are 1, 0.72 and 0.5. Figure 9 shows results for the case when the sensitivity factor is 0.72. The blue and red columns show income and profit/loss respectively for each quarter (TB). When the sensitivity factor is 0.72 and the quantity of sold CBF is 50 tons, the price for CBF is EUR 10.8/kg. This can be taken to be a breakeven price for CBF for the set of input parameters in Table 7. It has to be stressed that the outcome of the model depends entirely on the input parameters. With more accurate estimates of the input parameters, the model can be improved.

Table 7: Results of the Excel business model for years 2 and 3 of operation, for three values of the sensitivity factor.

Sensitivity factor	1		0,72		0,5	
Year	2	3	2	3	2	3
Equity	55%	58%	50%	52%	37%	30%
Profit of equity	14%	13%	0.3%	0.6%	-17.7%	-23.1%
Profit of share-holder equity	7.2%	7.1%	0.2%	0.3%	-7.7%	-8.6%

Figure 9: Results of the Excel business model for a CBF plant, showing income (blue) and profit/loss (red) for each quarter (TB)

1.10 Magnetic separation

It is known that iron oxides found in basalt present certain problems in the extrusion of basalt fibres. The problem is that one particular type of iron oxide (Fe_2O_3) reacts with the platinum-rhodium bushings used in the extrusion process. This causes excessive wear of the bushings, along with the associated cost of repairs and replacements. Icelandic basalt has a fairly high iron content and as a rule of thumb, about 90% of it is FeO and 10% Fe_2O_3 . Thus, Icelandic basalt contains a significant amount of Fe_2O_3 . It is therefore of some significance to determine whether iron-rich basalt grains can somehow be separated from the iron-poor basalt grains. One method that might be possible is magnetic separation.

A simple experiment was done on magnetic separation of basalt. A ground portion of sample HF-48 (fine powder) was placed in a container and a strong magnet was used

to find out how the powder was affected. The results are shown in Figure 10. The figure on the left shows the powder and magnet side by side. The figure on the right shows that after the magnet was placed on the powder, all of the powder stuck to the magnet. The magnet, with the powder stuck to it, was then shaken somewhat, so some of the powder fell off. The iron content of the powder that fell off, and the powder that stuck to the magnet, was then measured with an EDS method in a scanning electron microscope. The results of this experiment were as follows:

- Fe-oxides
 - 19.7wt% – Powder stuck to magnet.
 - 19.1wt% – Powder fell off.

The results show that the powder which fell off is not quite as iron-rich as the powder that stuck to the magnet.

The experiment shows first of all that the basalt powder reacts strongly to a magnet. Secondly, it shows that removal of iron rich grains might be a possible method to use in reduction of iron oxides in Icelandic basalt.

To further explore this topic, the first step would be to scan the open literature on the application of magnetic separation in practice. The second step would be to conduct experiments by applying this concept to Icelandic basalt.

Figure 10: The figure on the left shows powder and magnet side by side. The figure on the right shows what happened when the magnet was brought in contact with the powder. All of the powder sticks to the magnet

1.11 Conclusions

- A literature review, in addition to discussions with scientists in the field, has revealed the criteria for the composition and other properties that basalt has to meet in order to be suitable for production of CBF.
- A total of 154 samples of Icelandic basalt have been collected. Measurement of the chemical composition and evaluation of material parameters like acidity and viscosity moduli have shown that samples with andesite containing more than 50 wt% SiO₂ are best suited for production of CBF.
- Three samples have been chosen for the final stage of the selection process. The addition of burnt lime (CaO) is necessary to modify the chemical composition of these specimens in order to make them suitable for production of CBF. Experiments are being carried out on the modified material to determine its suitability for production of CBF.
- The viscosity of two of the samples was measured by Anton Paar in Austria. These measurements showed that both samples have the required viscosity in the required temperature interval to qualify for fibre drawing.
- Icelandic basalt contains a fairly high amount of iron oxide. A simple experiment on magnetic separation of a powdered sample was performed. The results of that experiment show that the material reacts strongly to a magnet. Further work is required to estimate the viability of using magnetic separation to reduce iron oxide content in Icelandic basalt.
- A rudimentary business model has been set up for a plant producing CBF in Iceland. The initial results show that for a plant producing 50 tons per year, the price of CBF needs to be at least EUR 11/kg in order to break even.

1.12 References

1. K. Singha. A short review on basalt fibre. *International Journal of Textile Science*, 1, 4, p. 19–28, 2012.
2. A.A. Vasileva, A.K. Kychkin, E.S. Ananeva and M.P. Lebedev. Investigation into the properties of basalt of the Vasilevskoe deposit in Yakutia as the raw material for obtaining continuous fibres. *Theoretical foundations of chemical engineering*, 48, 5, p. 667–670, 2014.
3. O.S. Tatarintseva, N.N. Khodakova and T.K. Uglova. Effect of iron oxides on the proneness of synthesized basaltic metals toward fibre formation. *Glass and Ceramics*, 69, 1–2, p. 71–74. 2012
4. A.G. Novitskii and M.V. Efremov, The technological aspects of the suitability of rocks from different deposits for the production of continuous basalt fiber. *Glass and Ceramics*, 69, 11–12, p. 409–412, March 2013.

5. N.N. Morozov, V.S. Bakunov, E.N. Morozov, L.G. Aslanova, P.A. Granovskii, V.V. Prokshin and A.A. Zemlyanitsyn. Materials based on basalts from the European north of Russia. *Glass and Ceramics*, 58, 3–4, p. 100–104, 2001.
6. Stekloplastic visit to Iceland. Boris Gromkov and Natalya Dementia. Personal communication. June 2014.
7. Lipex GmbH, Germany. Toni Schneider, Gert Lichblau. Personal communication. 2015.
8. Continuous Basalt Fibre, Reinforcing articles and basalt fibre materials production, market and forecast in the CIS. Sample PDF, Moscow, www.bavoma.com, October 2011.
9. A.V. Kochergin, N.V. Granovskaya, D.V. Kochergin, V.A. Savchenko and N.R. Galimov. Ways to supply gabbro-basalt raw materials to mineral fibre producers. *Glass and Ceramics*, Vol 69, No. 11–12, p. 405–408. 2012.
10. O.S. Tatarintseva and N.N. Khodakova. Obtaining basaltic continuous and staple fibres from rocks in Krasnodar Krai. *Glass and Ceramics*, Vol 67, No. 5–6, p. 165–168, 2010.
11. O.S. Tatarintseva, N.N. Khodakova, Uglova, *Glass and Ceramics*, Vol. 68, Nos. 9–10, p. 323–326, January 2012.
12. M.F.L. King, V. Srinivasan and T. Purushothaman. Basalt fibre: An ancient material for innovative and modern application. *Middle-East Journal of Scientific Research*. 22(2), p. 308–312, 2014.
13. A. Pisciotta, B.V. Perevozchikov, B.M. Osovetsky, E.A. Menshikova and K.P. Kazymov. Quality assessment of melanocratic basalt for mineral fibre product, southern Urals, Russia. *Natural Resources Research*, DOI: 10.1007/s11053-014-9253-9, 9 pages, 2014.
14. D. Pico, C. Wilms, G. Seide and T. Gries. Natural volcanic rock fibres. *Chemical Fibres International*. Vol 2, p. 90–91, 2011.
15. B.V. Perevozchikova, A. Piciotta, B.M. Osovetsky, E.A. Menshikov and K.P. Kazymov. Quality evaluation of the Kuluevskaya basalt outcrop for the production of mineral fibre, Southern Urals, Russia. *Energy Procedia* 59, p. 309–314, 2014.
16. O.S. Tatarintseva and N.N. Khodakova. Effect of production conditions of basalt glasses on their physicochemical properties and drawing temperature range of continuous fibres. *Glass Physics and Chemistry*. Vol 38, no. 1, p. 89–95, 2012.
17. D.D. Dzhegiris, M.F. Makhova, V.D. Gorobinskaya and L.N. Bombyr. Continuous Basalt Fibre. Translated from *Steklo i Keramika*, 9, p. 14–16, September 1983.
18. D. Giordano, J.K. Russell and D.B. Dingwell. Viscosity of magmatic liquids: A model. *Earth and Planetary Science Letters*, 271, p. 123–134, 2008.
19. Anton Paar, Austria. Dietmar Kroger. Personal communication, 2015.

2. Iceland Geosurvey – ISOR

Hjalte Franzson, Ögmundur Erlendsson and Björn S. Harðarson.

2.1 Geological setting

Iceland is located in the North Atlantic Ocean, and represents an island overlying a lower density mantle plume (hotspot) and lies also astride the Mid-Atlantic Ridge where rifting is taking place at a rate of about 1 cm/yr on average. The crust is therefore a mixture of an oceanic and a hotspot type. The basalt types range from tholeiitic to alkalic compositions, which are controlled by localized rifting conditions. Although basalt is far the most dominant rock composition, intermediate to acidic rock types are found within central volcanic complexes. The distribution is, however, bimodal with maxima at basalt (~90%) and rhyolite (~8%) and minima at intermediate compositions (~2% andesite). In terms of this project it implies that rocks which surpass 50% SiO₂ become rare until reaching near rhyolite compositions. Volcanic rocks which are found within continental regions and subduction zones do contain similar compositions. However, these often follow a more alkalic geochemical trend and a greater abundance of rocks of intermediate composition than found in Iceland.

2.2 Sampling criteria

During the initial preparation of the project and sampling, information was received from the Russian firm Steckloplastik, which is presently producing basaltic fibres. Representatives from the company were in contact with The Icelandic Innovation Centre which included a visit to Iceland to advise on sampling strategy. The project furthermore benefitted from communication with Alex Biland who works for US Basalt Corp. The Icelandic Innovation Center has also been in contact with the German company Lipex which has an extensive knowledge on basalt fibre technology.

Through these Steckloplastik and Lipex contacts, a guideline was set on the range of chemical compositions possible for basalt fibre production and these are shown in Table 1 (in the chapter by Innovation Center Iceland). To test the probability of finding

basalt that fell within these limits, an extensive ISOR data base was used for comparison. The NacTec database (Hopper et. al., 2014) includes 3997 full chemical analyses. The sample locations of these are shown in Figure 11, Figure 12 shows the samples that lie within the limits of Stekloplastik's guidelines while figure 13 shows those falling within the Lipex chemical constraints. Furthermore, additional information on the participation of some of the oxides in the formation of basalt fibres are known. Al_2O_3 apparently increases melting temperature. Iron oxides are of two types: in fresh volcanic rocks, about 10% are Fe_2O_3 and 90% are FeO . Progressive rock alteration leads to increasing ferric content. Generally, lower iron content is recommended, less than 10% is ideal but up to 15% is acceptable – the reason being that it affects the bushing where the fibres are formed.

Figure 11: A simplified geological map of Iceland with the locations of chemically analysed samples in the NacTec database

Figure 12: Samples from the NacTec database that lie within the Stekloplastic "chemical window". These contained about 50 locations

Figure 13: Samples from the NacTec data base that lie within the Lipex "chemical window". These contained about 75 locations constituting less than 3% of the total database

Iron oxides in Icelandic basalts and basaltic andesites are generally on the high side, where the majority surpass 10%. TiO₂ needs to be low, an upper limit of 2% is recommended, and this is assumed to be due to increasing probability of early crystallization of titanium oxides. Icelandic basalts and basaltic andesites are relatively high in TiO₂, many of which surpass 2%. Figure 14 shows the distribution of FeO(tot), TiO₂ and P₂O₅ plotted against SiO₂ for most of the samples. Very low values of P₂O₅ were recommended, probably due to the early crystallization of apatite in the melt.

Figure 14: Samples from the project. A) TiO₂ vs. SiO₂ B) P₂O₅ vs. SiO₂. C) FeO(tot) vs. SiO₂

Information on the recommended field character was gathered using a combination of data from Stekloplasik, Lipex, Alex Biland and our own deductive observations.

Lava flows were most commonly found. Their character should be fine grained. This condition was adhered to. Unofficial information from VTT reported the use of a coarse grained gabbro, but information on the success of this was not available.

Low vesicularity – This condition was considered to some extent. The meaning of this was not clear and had to be independently interpreted as follows: vesicles in Icelandic lavas show that the respective magma had been degassed during solidification. A vesicular lava was therefore not dismissed and could be sampled. A vesicular volcanic product which has been buried will undergo alteration according to temperature and permeability. That means that alteration minerals will occupy the vesicles in the rock

along with that high porosity will lead to preferential rock alteration. Alteration at temperatures $<230^{\circ}\text{C}$ will contain an appreciable amount of water bound in the alteration minerals and possibly some CaCO_3 . This will lead to degassing of H_2O and CO_2 release during the rock's melting, and may even cause differential melting points if alteration is heterogeneous, as these components cause lowering of the melting point of a rock. At a higher state of alteration, water (and possibly CO_2) will be greatly reduced in the altered rock, which in turn will lower the degassing component. The vesicularity was in general kept in mind during sampling, but not considered as a critical factor where no alteration was observed.

Hydrothermal alteration – We considered hydrothermal alteration not allowable due to degassing issues in the melting as described above. This is the main reason that sampling was largely confined to the volcanic zone and in areas of shallow erosion, and only to a minor extent outside where deeper erosion and more alteration is found. We may, however, have been too restrictive; in future, consideration should be given to an alteration state at temperatures higher than 250°C in deeply eroded, high-temperature fossil areas. Information on sample descriptions e.g. given by Alex Biland, with rock containing abundant epidote, amphibole and albite, implies high alteration but relatively low water content and was considered within sampling limits.

Hyaloclastite – Hyaloclastite is a rock type which is formed during an eruption underneath an ice-sheet, mostly during glacial episodes, and is a result of rapid quenching of magma. These range from larger fine grained basalt lobes to pillow basalts, pillow breccias and tuffs. This sequence also depicts crystallinity where the first is fine grained, pillow basalt is mostly crystalline but with glassy margins and volcanic glass between pillows. The third is a more heterogeneous mixture of crystallized fragments and glassy ground-mass. The tuff is usually $>90\%$ glass. In a way, quenching can be considered to be a magma that is “forcibly” cooled so rapidly that it does not have time to crystallize properly as those seen in lavas and intrusions. These rocks are, however, rarely totally formed of glass and contain crystallites in variable amounts. We would contend that hyaloclastites, despite showing somewhat heterogeneous crystallinity, should be considered as candidates for basalt fibre production. There may, however, be possible difficulty in regard to alteration. Glass is relatively sensitive to alteration, in particular with regards to the formation of palagonite. Palagonite is a “hydration” of glass and often occurs during the eruption. This hydration includes the addition of about 20% water which would indeed increase the “gas content” during the melting process. Some hyaloclastites, however, do only contain a very minor amount of palagonite.

Accessibility – A decision was taken to limit sampling to areas which were adjacent or less than approximately 500 m from a road. This is obviously an economical and even an environmental decision. It is also worth noting that an estimation of an accessible

volume was also made. Mountainous areas where layers extend into the mountains were therefore largely omitted.

Environmental issues – These issues will always have to be taken into account. The volcanic zone where some of the samples were taken will have to be considered specifically, particularly with the aim of placing prospecting operations in a less visible location. Numerous rock quarries are present, mainly associated with the Icelandic Road Service. Figure 15 shows the distribution of such bedrock quarries. Samples were also taken when other conditions were met, but in general most of them were not considered applicable. In order to mine, obtaining permission from the respective landowner is necessary. During sampling these issues were not dealt with, but they will have to be addressed when the final location has been decided upon.

Figure 15: Distribution of rock quarries used by the Icelandic Road Service (Icelandic Road Service database)

Figure 16 shows the location of all the samples taken by the participants as indicated in Table 4. The majority of the samples were taken in the south and southwest regions of Iceland, in part due their accessibility from Reykjavík. Some samples were though taken in the northwest and a few in northern, eastern and southeast Iceland. Each sample has an identity number. In table 8, sample identity, number and co-ordinates are displayed.

Three samples were selected for further testing as discussed in the previous chapter. Two are from two lava patches from the Hekla volcano: the 1970 and 1845 eruptions and the third is from the ~5 Ma old andesite lava belonging to the Brekkufjall phase within the Hafnarfjall-Skarðsheiði central volcano (Franzson, 1978). The difference between these two locations are that the former features completely fresh rocks while the latter is mildly geothermally altered.

The outcome of the sampling did not quite reach the goal of finding the ideal composition for basalt fibre production. However, if putting additives into the basalt to change the viscosity and acidity modulus is an option, it gives an extra degree of freedom in selecting basalt that meets all of the necessary requirements.

Figure 16: Simplified geological map of Iceland and location of samples

Table 8: Sample identity, number and co-ordinates for all samples from the study

Sample	Sample number	POINT_X	POINT_Y
NMI-2013	1	-19,97132167	63,60565955
NMI-2013	2	-19,98587578	63,62594221
NMI-2013	3	-20,63905259	64,06891578
NMI-2013	4	-20,64275732	64,0628197
NMI-2013	5	-20,84920342	64,14650993
NMI-2013	6	-19,92298533	63,98270132
NMI-2013	7	-19,90077806	63,99779515
NMI-2013	8	-19,87391279	64,11727148
NMI-2013	9	-19,8951367	64,11239456
NMI-2013	10	-20,26043667	64,08522325
NMI-2013	11	-20,34921345	64,03609003
NMI-2013	12	-21,05502248	63,95845439
NMI-2013	13	-21,38708403	63,86215843
NMI-2013	14	-21,45378381	63,90425663
NMI-2013	15	-21,44751045	63,90650131
NMI-2013	16	-21,76874937	63,87738053
NMI-2013	17	-22,07924476	63,86657682
NMI-2013	18	-22,56520462	64,02581548
NMI-2013	19	-22,48762275	63,97154148
NMI-2013	20	-22,069113	63,86230381
NMI-2013	21	-21,75667655	64,52742918
NMI-2013	22	-21,75453607	64,53032785
NMI-2013	211	-21,75408586	64,534624
NMI-2013	26	-19,84028567	64,03563933
NMI-2013	30	-18,59514126	63,49839678
NMI-2013	29	-19,76520162	64,01763417
NMI-2013	31	-19,68815045	65,77217524
RU-2014	38	-15,00908534	64,2433124
RU-2014	39	-21,63057939	65,63983267
RU-2014	40	-22,71455118	66,04007451
RU-2014	41	-22,30754088	65,88302203
RU-2014	42	-21,39836662	65,06132627
RU-2014	43	-23,6961248	65,64427401
HF-ISOR-2014	127	-21,726067	64,56065
HF-ISOR-2014	129	-21,7217	64,556483
HF-ISOR-2014	130	-21,7365	64,569233
HF-ISOR-2014	134	-21,668467	64,575683
HF-ISOR-2014	136	-21,666183	64,5756
HF-ISOR-2014	137	-21,665967	64,5754
HF-ISOR-2014	138	-21,665817	64,575167
HF-ISOR-2014	139	-21,6583	64,573833
HF-ISOR-2014	140	-21,668967	64,5609
HF-ISOR-2014	141	-21,693017	64,530683
JEI-2014	JEI-K23	-18,86472	63,6075
JEI-2014	JEI-L24	-20,239797	63,571991
BH-ISOR-2014	KE	-23,35999616	66,17310231
BH-ISOR-2014	SU	-23,36676982	66,08077066
BH-ISOR-2014	FF	-23,51122833	66,05489767
BH-ISOR-2014	GL	-18,56964557	65,50747843
BH-ISOR-2014	AF	-18,6445259	65,4667355
BH-ISOR-2014	KG	-18,21840671	65,65396004
ERP-RU-2015	E01	-23,63916667	65,6617
ERP-RU-2015	E02	-23,67856667	65,64566667
ERP-RU-2015	E02	-23,67856667	65,64566667
ERP-RU-2015	E03	-23,67801667	65,64565

Sample	Sample number	POINT_X	POINT_Y
ERP-RU-2015	E04	-23,6789	65,64583333
ERP-RU-2015	E05	-23,67843531	65,6453712
ERP-RU-2015	E06	-23,84557897	65,61696636
ERP-RU-2015	E07	-23,84536386	65,61680675
ERP-RU-2015	E08	-22,52835157	63,90906905
ERP-RU-2015	E09	-23,72489644	64,90034802
ERP-RU-2015	E10	-21,81102557	64,30485465
ERP-RU-2015	E11	-14,96640144	64,24300606
ERP-RU-2015	E12	-16,81976358	65,63777326
HF-ISOR-2015	HF1	-16,211611	65,61872601
HF-ISOR-2015	HF10	-14,45212204	65,29844997
HF-ISOR-2015	HF11	-14,51261801	64,65563896
HF-ISOR-2015	HF12	-15,40286103	64,29295301
HF-ISOR-2015	HF13	-15,62649096	64,26377702
HF-ISOR-2015	HF14	-15,63098098	64,264679
HF-ISOR-2015	HF15	-18,16688597	63,78567796
HF-ISOR-2015	HF16	-18,039574	63,78606303
HF-ISOR-2015	HF17	-21,48720399	64,05107601
HF-ISOR-2015	HF18	-21,42042596	64,02568102
HF-ISOR-2015	HF19	-20,77415197	63,94496899
HF-ISOR-2015	HF2	-16,36621999	65,64085096
HF-ISOR-2015	HF20	-20,769929	63,94543796
HF-ISOR-2015	HF21	-20,75468198	63,94714502
HF-ISOR-2015	HF22	-20,73555004	63,94823902
HF-ISOR-2015	HF23	-20,66044299	63,92604299
HF-ISOR-2015	HF24	-20,65783496	63,92435404
HF-ISOR-2015	HF25	-20,64771096	63,91961197
HF-ISOR-2015	HF26	-20,64574499	63,91894997
HF-ISOR-2015	HF27	-20,60246503	63,93527096
HF-ISOR-2015	HF28	-20,59951301	63,93800497
HF-ISOR-2015	HF29	-20,59201196	63,92006904
HF-ISOR-2015	HF3	-15,54309597	65,45530303
HF-ISOR-2015	HF30	-20,58540601	63,92336204
HF-ISOR-2015	HF31	-20,56863802	63,92584903
HF-ISOR-2015	HF32	-20,54038497	63,92730396
HF-ISOR-2015	HF33	-20,51379799	63,95437801
HF-ISOR-2015	HF34	-20,51494103	63,95481999
HF-ISOR-2015	HF35	-20,51261899	63,95380897
HF-ISOR-2015	HF36	-20,41416097	63,95208498
HF-ISOR-2015	HF37	-20,45692401	63,91832803
HF-ISOR-2015	HF38	-19,73783903	64,12296197
HF-ISOR-2015	HF39	-20,30009097	64,07463997
HF-ISOR-2015	HF4	-15,46056398	65,52347498
HF-ISOR-2015	HF40	-20,51384602	64,10440402
HF-ISOR-2015	HF41	-20,54419597	64,13723099
HF-ISOR-2015	HF43	-20,63116701	64,12913298
HF-ISOR-2015	HF44	-20,44762203	64,18296299
HF-ISOR-2015	HF45	-20,40411199	64,195447
HF-ISOR-2015	HF46	-20,40429203	64,195663
HF-ISOR-2015	HF47	-20,34408398	64,14938098
HF-ISOR-2015	HF48	-20,34932703	64,14888402
HF-ISOR-2015	HF49	-20,37510096	64,16761103
HF-ISOR-2015	HF5	-15,46084997	65,52804404
HF-ISOR-2015	HF50	-20,35900201	64,197302
HF-ISOR-2015	HF51	-20,331475	64,22019096
HF-ISOR-2015	HF52	-20,27254301	64,264104
HF-ISOR-2015	HF53	-20,25558701	64,27197604

Sample	Sample number	POINT_X	POINT_Y
HF-ISOR-2015	HF54	-20,25641497	64,260638
HF-ISOR-2015	HF55	-20,22349597	64,23948501
HF-ISOR-2015	HF56	-20,74873502	64,00167902
HF-ISOR-2015	HF57	-19,53381596	64,20582597
HF-ISOR-2015	HF571	-19,51779597	64,21409698
HF-ISOR-2015	HF58	-19,51780401	64,21407703
HF-ISOR-2015	HF59	-19,34352002	64,29427701
HF-ISOR-2015	HF6	-15,460308	65,50530201
HF-ISOR-2015	HF60	-19,34801297	64,29370997
HF-ISOR-2015	HF61	-19,35081001	64,30077299
HF-ISOR-2015	HF62	-19,401502	64,26567502
HF-ISOR-2015	HF63	-19,56854101	64,20411799
HF-ISOR-2015	HF64	-19,620743	64,16584496
HF-ISOR-2015	HF65	-19,89172298	64,13380003
HF-ISOR-2015	HF67	-20,18092504	64,13138
HF-ISOR-2015	HF68	-21,57659699	64,12711303
HF-ISOR-2015	HF7	-15,458136	65,50552002
HF-ISOR-2015	HF70	-21,96801301	64,04663502
HF-ISOR-2015	HF71	-21,95885	64,03874698
HF-ISOR-2015	HF72	-21,88658601	63,99798897
HF-ISOR-2015	HF73	-21,94197002	63,973403
HF-ISOR-2015	HF731	-21,941967	63,97340401
HF-ISOR-2015	HF74	-22,17342001	64,01714204
HF-ISOR-2015	HF75	-22,36914299	63,98174199
HF-ISOR-2015	HF76	-22,70574303	63,95488302
HF-ISOR-2015	HF76A	-22,704889	63,95398096
HF-ISOR-2015	HF77	-22,68291199	63,86831003
HF-ISOR-2015	HF78	-22,69307697	63,83180701
HF-ISOR-2015	HF79	-22,47994202	63,83542003
HF-ISOR-2015	HF8	-14,90557596	65,34696802
HF-ISOR-2015	HF80	-22,44950498	63,86103203
HF-ISOR-2015	HF81	-22,40934201	63,90407997
HF-ISOR-2015	HF82	-22,36913402	63,851982
HF-ISOR-2015	HF83	-22,36984204	63,85205199
HF-ISOR-2015	HF84	-22,23395797	63,85338698
HF-ISOR-2015	HF85	-22,15579798	63,85385703
HF-ISOR-2015	HF86	-21,70508998	63,84880803
HF-ISOR-2015	HF87	-21,38795497	63,84357001
HF-ISOR-2015	HF871	-21,38797903	63,84357696
HF-ISOR-2015	HF9	-14,68429699	65,38886497
HF-ISOR-2016	197	-16,387442	66,07066
HF-ISOR-2016	198	-16,411587	66,266016
HF-ISOR-2016	200	-16,402924	66,275836
HF-ISOR-2016	202	-16,799664	65,690239
HF-ISOR-2016	203	-16,751294	65,726827
HF-ISOR-2016	204	-16,755623	65,72654
HF-ISOR-2016	205	-16,459943	65,655111
HF-ISOR-2016	206	-16,466208	65,656441
HF-ISOR-2016	233	-20,231022	63,438174
HF-ISOR-2016	234	-20,228238	63,436118
HF-ISOR-2016	235	-19,897747	63,996781
HF-ISOR-2016	236	-19,616564	64,077173

2.3 References

- Hjalti Franzson 1978: Structure and Petrochemistry of the Hafnarfjall-Skarðsheiði Central Volcano and the Surrounding Basalt Succession, W-Iceland. Ph.D thesis at the University of Edinburgh, 267p.
- Hopper J. R., Funck T., Stoker M., Ártíng U., Peron-Pinvidic G., Doornenbal H. & Gaina C. 2014. *Tectonostratigraphic Atlas of the North-East Atlantic Region*. GEUS, Copenhagen, Denmark.

3. Reykjavik University – RU

Eythor Rafn Thorhallsson

3.1 Tasks done by Reykjavik University members

3.1.1 *Sample collection*

Three field trips to collect basalt samples were scheduled in cooperation with ISOR. One field trip was to the Reykjanes Peninsula and the other trips were to the Northeast and Northwest of Iceland, respectively. During these trips several dozen samples were collected.

The samples were taken from mines and also from basalt lava fields that appeared promising.

3.1.2 *Basalt fibre manufacturing*

Work was carried out in order to gain a better understanding of basalt fibre production by using an electrical furnace. There was especially much interest in new techniques using induction furnaces. Data were collected from basalt fibre producers and companies supplying necessary equipment for the production.

3.1.3 *Computational simulations on basalt fibre reinforcement*

Work was carried out to simulate experimental research performed in previous years by using the non-linear program ANSYS. These previous research projects from Reykjavik University were performed on concrete beams reinforced with basalt fibre rods at their tension sides. The beams had both slack bending and pre-stressed tendons. Previous research on strengthening concrete columns was also of interest. The results were compared and analysed. The main objective was to build a computer model that could be used to design concrete elements with basalt fibre rods and mats.

3.1.4 *Basalt Reinforced Concrete Sandwich Panels*

Thin concrete panels of 20 mm thickness were designed and tested. The reinforcement in the panels consisted of a basalt fibre net instead of steel reinforcement. The potential use of the panels is in simple buildings and also as a façade on in-situ reinforced buildings. The concrete class was designed, as well as the manufacturing process. The panels were tested when they had reached 28-day strength in a four point bending test. The panels showed elastic behaviour. The basalt net in the middle of the panels appeared to perform as expected. The main conclusion to take away is that these thin panels with basalt fibre nets can indeed be built and present a very interesting option for the building market.

3.1.5 *Basalt reinforced glulam beams*

24 Glulam beams (3.2 m long, 65 mm wide and 167 mm high) were tested in a four-point bending test. The beams were reinforced with basalt fibres under the bottom lamella. The test results were compared with an analytical model to predict the moment capacity. The experimental results compare relatively well to the mathematical model. Strengthening glulam beams on the tension side with FRP materials increases bending stiffness and bending strength. An increased reinforcement ratio, in the form of additional fibre cloth layers, had a significant effect on both the strength and the stiffness. Strengthening the glulam beams on the tension side allows for a potential reduction of the cross-section, or lower timber grade, while maintaining the same bending strength and stiffness as for the unreinforced beam.

3.1.6 *Basalt Reinforced Asphalt roads*

The research project was conducted in collaboration with the Innovation Center Iceland (ICI). The aim was to determine whether there was a reduction in deformation when placing basalt fibres inside asphalt. A test was set up and devised in accordance with applicable standards, running 10,000 times across the sample. Based on the results, it is our belief that basalt fibre nets can significantly reduce the formation of wheel-tracks in asphalt. However, it has been claimed that the main reason for the formation of wheel-tracks in asphalt is due to studded tires in countries where they are allowed. Nonetheless, there is considerable interest in investigating the impact on heat generated expansion of asphalt by placing basalt fibres in the asphalt.

3.1.7 *Fire resistance and freeze-thaw durability of fibre reinforced concrete*

It is well known that the addition of PP fibres improves the fire resistance of concrete, but it also may slightly decrease its compressive strength characteristics. With this in mind, we tested basalt fibres and compared them to PP fibres. It can be concluded that the addition of chopped basalt fibres decreases the workability of fresh concrete. The idea had been that chopped basalt fibres would strengthen cement paste and that the decrease of its strength due to fire exposure would not be dramatic. This idea, however, was not proven, probably owing to an insufficient addition of basalt fibres. The improvements in terms of properties were not impressive enough to make any solid conclusions. We recommend that basalt fibres be tested in a higher amount, or added by volume not by weight.

3.1.8 *International research cooperation*

Eythór Thorhallsson and Jonas Snæbjörnsson are national members in the COST group TU1207 Composite Material for Concrete Structures. The aim of the work is to publish design guidelines for composite materials for concrete structures.

3.1.9 *RU Research members in GREENBAS*

- Associate Professor Eythor Rafn Thorhallsson.
- Professor Jónas Snæbjörnsson.
- Professor Ólafur Wallewik.
- Dr. Todor Zhelyazov, Visiting research fellow from Bulgaria.
- Assistant Professor Indriði Sævar Ríkharðsson.

3.1.10 *RU Students in GREENBAS*

- Andri Gunnarsson, MSc.
- Þórdís Björnsdóttir, BSc.
- Benedikt Rafnsson, BSc.
- Guðmundur I. Hinriksson, MSc.
- Álvaro E. Garramiola Bilbao, Erasmus student.
- Sigurður Halldór Örnólfsson, BSc.
- Stefán Ingi Björnsson, BSc.
- Guðmundur Úlfar Gíslason, BSc.
- Iveta Nováková PhD student.

4. JEI

Árni B. Árnason

4.1 Collection of Samples

Field trips to collect basalt samples were scheduled in cooperation with ISOR. One field trip was to the Reykjanes Peninsula and four trips were to southern Iceland's lowlands. Samples were collected at the areas surrounding Mt. Hekla and at Myrdalssandur near Mt. Katla. Further sampling was carried out at Þórlákshöfn and at Landeyjar.

4.2 Basalt Fibre Manufacturing

JEI was involved in work done at Reykjavik University in compiling information on the different stages of manufacturing basalt fibres and the various manufacturing processing methods. The fundamental issues in production described based on the key operations which are shared with all production methods are as follows:

Raw material preparation – This addresses matters including the selection of suitable quarrying methods, logistical issues with regard to potential locations for production, types of mining and transportation machinery along with purchasing and operational costs. Further matters in addition to the aforementioned include general mining and transportation expenses, power accessibility, power consumption and electricity cost calculations, comparison of electricity costs with costs in various European countries and with gas costs, waste and pollution estimations, requirements for and costs of production housing including ventilation systems, etc. An assessment was performed on the general production site accessibility for different sites. The initial results on raw material preparation were used to support the B.Sc. thesis of Benedikt Rafnsson.

Melting of rocks – This entails the comparison of different types of furnaces, earlier, recent and ongoing technical development and energy sources. As for bushings, developments in production of and renewability in different types of bushings, running costs are of relevance.

Melt homogenization – This relates to the importance of a uniform raw material and of a uniform melt.

Delivery of melt to bushings – This relates to the technical and economic aspects for various types of furnaces.

Drawing of melt through bushings – Physical aspects.

Drawing of elementary filaments – Physical aspects.

Application of sizing agent and spooling – The difference that various sizing agent types have on the end products. An investigation was done on recent development of continuous fibre products in which no sizing agent is used, as well as strength comparisons and the effect on the production costs and costs of final goods.

General factory layouts for existing factories were compared with potentially “ideal” layout sketches. Roller winders and drying procedures were examined. Descriptions of various applications of continuous fibre products and production methods, including ones for profile and tube production as well as a number of continuous fibre fabrics products, were also presented.

4.3 Basalt Fibre Market

JEI carried out an investigation into the market for basalt fibres.

Although still at a developmental stage, the global basalt fibre market is seeing considerable growth which is expected to meet growing demand from the building and construction industries. Non-corrosiveness, heat and fire resistance, as well as high strength come together to form the main basis for the increasing demand for basalt fibre products. The construction, transportation and shipping industries – requiring products that can tolerate high temperatures, have great chemical resistance, are strong and durable, and that have low water absorption properties – are the source of around three quarters of the global demand for basalt fibres.

Europe and North America are the largest consumers of basalt fibres. Russia, the United States, Germany, Belgium, and Ukraine are the leading countries in terms of demand. The main reason seems to be the high level of strategic initiative in the application industries in the North American and European markets. The well-established markets for carbon and glass fibres also affect the balance of usage of basalt fibres in different parts of the world. The volume used in Asia-Pacific industries is quite small, making up only around 15% of the global market in value, with the caveat that it is expected to increase significantly in the next years.

The predictable increase in high-tech production segments of the construction and automotive industries in Europe is expected to be a probable force in increasing the demand for basalt fibres.

In the last three to four years there has been a substantial increase in demand for basalt fibre from the Asia-Pacific, which is boosted by the electric and electronic industries. The high insulating qualities make basalt fibres useful for integration into printed circuit boards, insulating around ten times better than E-glass.

Imminent technological progress, developments for raw materials, and innovation are seen as the main influencing factors in the global basalt fibre market. Current costs and applications are also expected to be of great importance.

The value of the compound annual growth rate of the basalt fibre market is predicted to be 13.7% between the years 2015 and 2020.

These are firms in the forefront of the basalt fibre market today:

- Basaltex (Belgium).
- Sudaglass Fibre Technology (U.S.).
- Kamenny Vek (Russia).
- Zhejiang GBF Basalt Fibre Co., Ltd (China).
- Technobasalt (U.S.).
- Shanxi Basalt Fibre Technology Co., Ltd (China).
- Jiangsu TianLong Continuous Basalt Fibre High-tech Co., Ltd. (China).
- GMV China (China).
- Mafic SA (Luxembourg and Ireland).

4.4 Columnar Basalt

Due to JEI's quarrying equipment, manpower and raw materials processing facilities, the initial plan was for JEI at all times to be prepared to crush, screen, wash and then deliver basaltic rock for melting and continued testing. Neither processing nor delivery of larger quantities of processed basalt ended up happening.

Basaltic columns could be of particular interest as a possible raw material for the production of basaltic fibres due to their mineralogical homogeneity. One can safely assume that columnar basalt should be excavated differently and with more care than most other sources of basalt, partly due to environmental concerns. Accordingly, it is

generally held that detailed preparation for excavation is a necessity, in addition to the collection of data and updating of reports.

In order to prepare for any possible form of raw basalt mining and material processing, extensive updating and compilation of data from previous research conducted by JEI on basaltic columns and various deposits was performed and a special report was prepared.

4.5 International cooperation

Arni Arnason at JEI along with Eythór Thorhallsson at RU have been in contact with some of the leading companies in the basalt fibre industry.

They are: Mafic SA in Ireland (and Luxembourg), Isomatex in Belgium, Basalttex also in Belgium and US Basalt Corp in Texas, in the United States.

Meetings during the GREENBAS project were held with representatives from these firms in Europe.

All of the parties have interest in further collaboration.

5. SINTEF

Kamal Azrague and Marianne Rose Kjendseth Wiik

5.1 Objectives

The objective of this project was to carry out a lifecycle assessment (LCA) which evaluated the sustainability of continuous basalt fibre production in Iceland, compared to current Russian production, and to report and publish the obtained results. This included evaluating a range of different scenarios based on size and type of furnace, mine location and mode of transport. Furthermore, a comparison has been completed that assesses the environmental performance of competing, market-available materials, such as steel, glass fibre and carbon fibre. The analysis also investigated the second stage production of basalt fibre reinforced polymer (BFRP), with the addition of polyester resin in the production process. It has also looked at the use of BFRP as an alternative to steel reinforcement.

5.2 Continuous basalt fibre (CBF) production

Basalt is extracted from the mine using heavy machinery (bulldozer) then it is crushed and screened using crushers and vibrating screens. Basalt aggregates are then transported by truck to the CBF production factory. Overall, the manufacturing process of the CBF is similar to that of glass fibres. Basalt aggregates, as a raw material, are fed to the furnace where they are melted at 1,450–1,500 °C. Subsequently, the molten material is forced through platinum/rhodium crucible bushings to create fibres. While the drawing of continuous fibre occurs, their surface is covered with sizing agent which is a special coating in order to promote the association of fibres into a yarn, to reduce friction between fibres, and to improve the adhesive properties of fibres. The fibres are wound and dried before being packed for commercialisation (Sim *et al.*, 2005). Figure 17 shows the different steps involved during the mining of basalt and the CBF production.

Figure 17: Diagram of the CBF production process (Inman *et al.*, 2016)

5.3 Materials and methods

The used methodology follows the LCA-framework according to ISO 14040 standard. The framework is divided in four phases: 1) goal and scope definition which identify the purpose of the study, the foreseen product of the study, the system boundaries, and the functional unit; 2) Life cycle inventory analysis which consists of the collection, compilation, and analysis of the data; 3) life cycle impact assessment which evaluates the environmental impacts; 4) life cycle interpretation which consists of analysis and interpretation of the impact assessment and the inventory analysis to establish recommendations based on the goal and scope of the study.

During this study, the production chain is divided into four modules, namely: A1) extraction; A2) transport to production plant; A3) CBF manufacture; and A4) transport to customer for further processing.

Goal:

- Evaluate the environmental impacts for the production of CBF in an Icelandic context.
- Perform an analytical comparison of the gas based heating method to the electric method using renewable electricity from the grid in Iceland.
- Comparison of the Icelandic production to the Russian production.
- Comparison with other fibre materials (steel, glass fibre and carbon fibre).
- Comparison of the impacts from Ukrainian and Icelandic mines.
- Comparison of resins (polyester resin, epoxy resin) for BFRP production.

Scope: The boundaries of the system are selected to include the extraction of basalt raw material, transport of raw materials, and the manufacture of CBF/BFRP (see Figure 18). The functional unit was 1 kg of produced CBF/BFRP. For the life cycle inventory, two types of data have been used, real data and data from databases included in Simapro

with modifications to fit the Icelandic and Russian context. For the impact assessment, the software Simapro 8 and the ReCiPe Midpoint Hierarchist method were used.

Figure 18: Diagram showing the system boundary used

5.4 Results

The LCA performed on the mining of basalt aggregate shows that the main contributor to global warming (CO₂eq) is diesel and transport, as the mining in Iceland does not require heavy infrastructure or chemical explosives. Two mining scenarios were compared for the supply of raw basalt. The first is the supply from an Icelandic quarry and the second is from a Ukrainian quarry. Compared to the Icelandic basalt supply scenario, the Ukrainian basalt scenario has higher transport emissions, which would result in a slightly higher CO₂ footprint for the final produced CBF.

The comparison of the Icelandic production, where renewable electricity is used, to the Russian production, where non-renewable gas and electricity are used (see Figure 19), shows that the Icelandic production scenario has lower emissions than the Russian gas and electric production scenario (see Figure 20 and Table 9). In both cases, furnace energy consumption is identified as the largest contributor to emissions. The further reduction of furnace energy consumption is dependent on numerous parameters, such as the type of furnace, furnace size and CBF production rate. Energy input decreases with increased production capacity (kWh per kg of continuous basalt fibre produced) due to the increased size of the furnace, even though a larger furnace requires continuous operation and takes longer to heat up.

Figure 19: The different electricity mixes (Azrague *et al.*, 2016)

Figure 20: Results from the LCA of CBF production (Azrague *et al.*, 2016)

Table 9: Units and results for Figure 20

Impact category	Unit	Russian scenario	Iceland electricity + gas	Iceland only electricity
Global warming (GWP100)	kg CO ₂ eq	9.86E-01	3.41E-01	1.53E-01

In addition, the option of using chemical additives was assessed in terms of their environmental impacts. It was found that pure additives sourced locally are environmentally preferable to waste or industrial by-products.

Finally, a sensitivity analysis on different types of resin was performed in order to ascertain the environmental impacts of basalt fibre reinforced polymer (BFRP) to be used as reinforcement material instead of other conventional reinforcement materials such as steel, carbon fibre and glass fibres. The LCA results showed the largest contributor to BFRP emissions was resin (86.8%), followed by furnace electricity consumption (6.7%), mining (6.3%) and transport (0.1%).

5.5 References

- Kamal Azrague, Marianne Rose Inman, Lisbeth-Ingrid Alnæs, Reidun Dahl Schlanbusch, Birgir Jóhannesson, Thorsteinn Ingi Sigfusson, Eythor Rafn Thorhallsson, Hjalti Franzson, Arni B Arnason, Sirje Vares: "Life Cycle Assessment as a tool for resource optimisation of continuous basalt fibre production in Iceland" in "Life Cycle Assessment and Other Assessment Tools for Waste Management and Resource Optimization", Professor Umberto Arena, Second University of Naples, Italy Professor Thomas Astrup, Denmark Technical University, Denmark Professor Paola Lettieri, University College London, United Kingdom Eds, ECI Symposium Series, (2016). http://dc.engconfintl.org/lca_waste/10.
- Inman, M., Thorhallsson, E. R., Azrague, K. (forthcoming). A Mechanical and Environmental Assessment and Comparison Of Basalt Fibre Reinforced Polymer (BFRP) Rebar And Steel Rebar In Concrete Beams. *Energy Procedia*. ISSN: 1876–6102.
- ISO 14040: 2006. Environmental management – Life cycle assessment – Principles and framework; 2006.
- Sim J, Park C, Moon DY. Characteristics of basalt fibre as a strengthening material for concrete structures. *Compos Part B* 2005; 36: 504e12.

6. VTT

Sirje Vares, Anna Kronlöf, Pertti Koskinen and Tapio Vehmas

6.1 Objectives

Iceland has plentiful basalt resources, but their composition varies considerably. To use basalt for different kinds of applications, raw material processing is required. The objective of the VTT work within the GREENBAS project was to theoretically study Icelandic basalt modifications with different additives to adjust desirable oxide composition for the production of continuous basalt fibres.

The parameter for the assessment of basalt mixes for CBF production is the resource efficiency. This is not just essential for the basalt mine, but also for the raw mineral materials required as additives in CBF production. Resource efficiency means efficient use of energy, natural resources and materials in order to create products and services with fewer resources and environmental impacts. Resource use was studied using the life cycle assessment method (ISO 14040) and via life cycle stage “production” (comprising sub-stages: raw material productions for basalt mix and raw-material transportation to the CBF plant). Resource use indicators were calculated for the adjusted Icelandic basalt mixes applicable for continuous basalt fibre production. Main indicators used for resource consumption and consequent impacts were: Abiotic resource depletion potential (as an antimony equivalent), Abiotic resource depletion potential for fossil fuels (ADP kg Sb eq and ADP-fossil fuels – MJ), use of primary material (kg), use of water (kg), waste generation (kg) and greenhouse gases (kg GHG).

6.2 Tasks

VTT work was related to the work packages: WP1 (mining and production), WP 2 (sustainable use of energy and resources) and WP3 (life cycle analysis).

Material resource efficiency was defined for CBF production. The main goal was first to gain understanding about the basalt oxide composition and properties required for good quality and sustainable continuous basalt fibre production. Work started with

proposing a simplified method for the adjustment of main basalt oxides with additional minerals and continues with the resource use efficiency calculation and tool creation.

VTT study can be divided into the following sub-tasks:

- State of the art study.
- Study of Icelandic basalt mines and selection of additional minerals for the basalt mix adjustment.
- Overview about the Nordic sources of those minerals.
- Study of selected mineral production methods and resource consumption assessment.
- Resource consumption assessment for the adjusted basalt mixes.
- Slag management in the production process of continuous basalt fibres.

6.3 Main results

6.3.1 *Modification of Icelandic basalt*

WP1 involved studies of the rock materials from 154 mines that are mostly situated around the volcanic zones throughout the country. Numerous literature studies show requirements for the raw materials used for continuous basalt fibre production. According to the Russian and Chinese CBF production studies [1, 2, 3, 4, 5], Icelandic basalt does not fulfil these requirements and modification with additional minerals will be needed. VTT's work considered basalt modification criteria.

The desired target composition of the melt is controlled by the manufacturing process of continuous fibres. Different production methods have different criteria for the basalt melt composition. Selection of additional minerals should be based on the understanding of causalities between the versatile parameters and production method. Some main discontinuities of basalt melt are listed below:

- Melting point – Each additional material needed for the mix adjustment consists of several minerals, each having different melting points. Each mix component needs to achieve its melting point before entering into the melt phase. The additive materials should have a low melting point or one identical to basalt. The minerals with high melting points should be ground as finely as possible and the presence of oversized particles should be avoided.

- Problems related to the “shot” or “bead” formation – Instead of forming fibres, the melt produces spherical particles called shots. This phenomenon is described by Mohan, A [6]: “Our experiments revealed that viscosity of the solution, the speed of the external drum, the collecting distance, surface tension of the solution, net charge density and the electric field play an important role in the formation of shots”.
- Existence of non-metallic oxides (P, S) – These tend to decompose as gaseous oxides forming bubbles in the melt. Such oxides should be avoided because during the solidification process, the bubbles break the fibre. Titanium, chromium and nickel oxides have extremely high melting points and therefore are also to be avoided.

The requirements set for the basalt oxide composition, acidity modulus, and viscosity are the criteria for successful CBF production. The basalt source, along with the raw material type used for the basalt mix modification, together have an impact on the efficiency, although it should be stated that efficiency also depends on the process productivity, frequency in fibre breakage, waste generation and from the possibility to utilize production slags. The mix design for Icelandic basalts and raw-materials for modification were determined in accordance with the target mix from Ukraine (Basalt 33), suitable for CBF production (see Table 10).

Table 10: Chemical composition of Ukrainian basalt 33

Oxide	wt%
Na ₂ O	4.3
MgO	2.9
Al ₂ O ₃	20.5
SiO ₂	51.8
K ₂ O	1.9
CaO	8.6
MnO	0.0
P ₂ O ₅	0.0
TiO ₂	1.2
FeO	8.8
Acidity index (SiO ₂ +Al ₂ O ₃)/(CaO+MgO)	6.3

The chemical composition of the Icelandic basalts is shown in Figure 21. When plotted against the CaO+MgO content it becomes obvious that those Icelandic basalts form two groups separated by a gap in the x-axis (CaO+MgO content) between the values of 7.5% and 12%. The four Ukrainian basalts, which all used for CBF production, fall into the gap range.

Figure 21: The chemical composition of the Icelandic basalts and Ukrainian basalts (Ukrainian basalts are used for continuous basalt fibre production)

The mix designs for Icelandic basalt modification are shown in Figure 22, results are shown Figure 23 (for the main elements) and Figure 24 (for the trace elements). When a single basalt source is utilized, the amount of admixture is in the range of 20–30%. If two basalt sources are mixed (total addition is larger, + 40%), the amount of needed admixtures will reduce to below ten percent. With further optimization, it was suggested that only minor amounts of admixtures are needed.

Figure 22: Basalt mix designs with the larger additions (+40% of additions, containing complementary basalt and additives like metakaoline, CaO, aluminate cement and quartz). On the X-axis the CaO+MgO content of the original basalt

Figure 23: The result of the basalt mix with the larger additions, main elements (+40% of additions, containing complementary basalt and additives like metakaoline, CaO, aluminate cement and quartz). On the X-axis the CaO+MgO content of the original basalt and on the Y-axis adjusted chemical composition and acidity module

Figure 24: The result of the basalt mix with the larger additions, trace elements. (+40% of additions, containing complementary basalt and additives like metakaoline, CaO, aluminate cement and quartz). On the X-axis the CaO+MgO content of the original basalt and on the Y-axis adjusted chemical composition

6.3.2 Resource consumption

Industrial mineral studies demonstrate that some of the proposed minerals show less resource consumption than others. Production of industrial minerals consumes fuels and results in emissions and waste. In addition, carbonate minerals contain decomposing carbonates and thus additional CO₂ emission will be released during the production process. This causes higher GHG emissions. For example, 1.7 kg of calcite is needed for 1 kg of calcium oxide production because during the process calcium carbonate decomposes into calcium oxide and CO₂ emission. If the process emission could be recovered elsewhere, then calcite input could be allocated between those two products (CaO and CO₂) and thus the raw material amount allocated for CaO production would be less than in case when all calcite (1.7 kg) was allocated to the production of CaO.

Figure 25 shows resource use and Figure 26 shows ADP for 1000 kg of basalt mix at the CBF production plant. In the case where the basalt was suitable for production of CBF, for every 1 ton of raw material approximately 1 ton of basalt would have been used. In Icelandic basalt, the chemical composition of the basalt was adjusted with minerals and this increases raw material consumption from 1 to 10%. Differences between the different basalt mixes in abiotic resource depletion are much higher.

Figure 25: Resource use for 1,000 kg basalt mix at plant

Figure 26: Abiotic resource depletion (ADP as antimony-eq, according to CML 2001 method [7])

The selection of the basalt for CBF production should be based not only on the adjustment of oxide composition but also on availability, grindability, concentration and distribution of harmful trace elements as well as their effect on the process. The role of

alkali metals in flux formation and the effect on the melting point should also be considered. Thus the result for basalt adjustment in the GREENBAS project is not likely conclusive. In order to understand the causalities between the versatile parameters, the GREENBAS project needs to proceed towards multifunctional analysis of the trace elements as well as performance testing in pilot scale production.

6.3.3 *Overview of Nordic sources for production of basalt fibres*

An availability study for the additives possibly needed for Icelandic basalt modification was performed. These additives can be found from pristine minerals, industrial by-products and recycled materials. It is obvious that resource efficiency in CBF production will be improved by using by-products, recycled materials or even waste materials. However, waste materials typically contain heavy metals as well as other trace minerals that may jeopardise the basalt fibre production process. The most practical method for basalt modification is to use industrial minerals instead of waste materials. All potentially needed minerals could be found in Nordic countries and they do not entail the depletion of precious resources.

- The best source for silicon is quartz filler, silica fume and pumice. These are largely available in Finland, Norway and Iceland. SiO_2 is also a by-product of the ferrosilicon industry in Iceland.
- The best source for aluminium is kaolin and wollastonite. These materials are mined in Denmark and Finland. In three aluminium smelters in Iceland there are Al_2O_3 oxides in the raw material stream as well as in the dross.
- The most promising recycled material is glass waste which is ready processed and contains large amount of silicon.
- The best source for calcium is limestone, which is available in the Nordic countries. One local source for calcium could be sea shells which are readily available in Iceland.

6.3.4 *Waste management*

A waste management study was carried out by using data from the relevant literature and on the basis of VTT's earlier slag related research. According to the literature, continuous basalt fibre production is environmentally friendly from a waste management perspective. CBF production does not generate a lot of slag if the raw material is carefully selected and adjusted. The typical slag composition of CBF processing contains

unfused basalt and molten iron impurities which are difficult to melt. The composition of the slag depends also on the selected CBF production process as some processes are more efficient in melting.

Icelandic basalt has a higher content of iron than typical high quality CBF. Depending on the scenarios applied for the handling of this high iron content, iron could end up in slags and in pre-treatment solutions. The scenarios for managing iron content in Icelandic basalts are:

- CBF production with high iron content – the iron ends up in the product.
- Pre-treatment of the raw material to extract the excess iron – the iron ends up in the pre-treatment solution.
- Iron segregation in the molten phase – iron ends up in the slag.

The comparison of produced CBF composition with the Icelandic basalt composition gave an indication about the elements that could be detected in the slag. The comparison shows that the slag might be rich in silicon and titanium, but that the content of alkalis is small. Elements are intermixed with unfused basalt. The main conclusion is that CBF production slag can have a composition that can be recycled back to CBF processing or it could be utilized in similar applications where slags are typically used (for example, in concrete).

6.4 Conclusions

- The chemical composition of Icelandic basalts needs to be modified for CBF production. According to the results, all basalts could be modified to achieve desired oxide composition.
- For the modification, additional aluminium silicate and calcium aluminate will be needed. It was suggested to use complementary basalt, metakaoline, CaO quartz and aluminate cement. Use of waste materials was avoided as they typically contain heavy metals as well as trace minerals that may jeopardise the fibre production process.
- With the complementary basalt, the need for other additional materials is reduced; typically, the amount is around 10% or less. The number can be further reduced by careful selection of the combined basalts.
- The final selection of the basalt should be based also on other criteria: availability, grindability, concentration and distribution of harmful trace elements as well as

their effect on the processing, the role of alkali metals in flux formation and the effect on the melting point.

- All of the additives needed for the modification are available in Nordic countries and do not contain precious elements.
- CBF production does not produce much waste if the raw material is carefully selected and adjusted. CBF production slag can have a composition that can be recycled back to the CBF process or it can be utilized in similar applications where slags are typically used (for example, in concrete).
- Basalt composition in different deposits varied and the need for the additive type and amount is also varied. Additives increased the resource use of basalt mix by 1–10% compared to when their addition was not necessary.
- Adjusted basalt mixes show significantly varied abiotic resource depletion. At a minimum, it was 0.14 kg/1,000 kg mix and at a maximum, 0.67 kg/1,000 kg mix.
- The GREENBAS project needs to proceed towards multifunctional analysis of the basalt trace elements, performance testing in pilot scale production, and best additive selection.

6.5 Information on the importance of the project for the sustainable raw materials sector

The GREENBAS project has investigated the sustainable production of CBF from basalt mining. The sustainability criteria for CBF production are:

- location of the basalt sources.
- renewable energy use in an energy intensive production method.
- utilization of resource efficient minerals for the basalt mix adjustment.
- utilization of CBF production slags.
- minimization of production wastes.

As continuous basalt fibre production can be classified as an energy intensive process, precise selection of raw materials and production methods is essential for the efficient handling of raw-material sources, product quality and energy savings. Oxide composition, viscosity, acidity and other material properties, as well as resource efficiency and

environmental impacts are essential criteria in the selection of basalt mines for sustainable CBF production.

In basalt mix optimisation with additional minerals, some raw materials could be obtained from the already existing metals industry in Iceland. As an example, SiO_2 is a by-product of ferrosilicon production. SiO_2 fines could be added to a natural basalt mix in order to increase its silicon component. There are also three aluminium smelters in Iceland where Al_2O_3 oxides are present in their raw material stream as well as in the dross. If local materials from metal industry can be efficiently utilized in CBF processing, then long transportation distances from overseas with their associated impact from fuel consumption would be avoided.

A detailed understanding was gained within the GREENBAS project about the raw-materials needed for CBF production. It is likely that mines suitable for basalt fibre production can be found in Scandinavia as well. Understanding of CBF raw material properties, their resource efficiency and environmental impact is useful for the selection of local raw materials and additives from Scandinavia or for setting up a sustainable CBF production unit in some other Nordic country.

6.6 Dissemination

The project studied the theoretical possibility of mixing basaltic materials with other material additives to achieve the optimal chemical composition for CBF production in Iceland. The project is ready to start small-scale, all-electric pilot testing with the goal of further developing second stage production. The GREENBAS project results will be utilized in project's next stage: NORBAS (if the project gets funding for continuation).

All presentations made during the GREENBAS project are available on the GREENBAS public webpage. VTT contributed by preparing a set of 10 presentations.

The GREENBAS tool was created for basalt modification and this will be used and tested in the NORBAS project.

VTT report is drafted and to be published in the series of VTT Technology reports.

The journal paper about CBF production in Iceland will be prepared together with the GREENBAS project consortium.

6.7 Information on the societal implications of the project

The societal implications of the work at VTT centre around improved scenarios for the practical utilization of basaltic raw material in the fibre industry as well as the potential for improved material efficiency.

6.8 Information on the importance of the project results to the Nordic region

Currently Nordic countries do not have a continuous basalt fibre production industry. The GREENBAS project generated data related to CBF production and the sustainable use of raw materials in Iceland. The assessment procedure and experience gained in this project could also be applicable in other Nordic countries for the adjustment of basalt mix composition and setting up resource efficient CBF production.

6.9 References

- [1] Data from Stekloplastics. Stekloplastic visit to Iceland. Communication with Stekloplastics Boris Gromkov and Natalya Demenia with Birgir Jóhannesson. June 2014
- [2] RU 2421 408 C1. Osnos, S & Osnos, M. Method of producing continuous fibres from basalt rocks. Date of publication: 23 November, 2009.
- [3] Xie Ergai, Li Zhongying. Application prospect of basalt fibre, *Rbier Composites*, 3 (2003), 17–20 p.
- [4] Li Jianjun, Dang Xinan. Preparation of continuous basalt fibre, *China Synthetic Fibre Industry*, 30(2007), 35–37 p.
- [5] Liu Yanchu, Wang Fen, Li Jianjun. Study on continuous fibre made from basalt of Lueyang, *Bulletin of the Chinese Ceramic Society*, 27(2008), 160–164 p.
- [6] Mohan, A. Formation and Characterization of Electro spun Nonwoven Webs. Thesis. North Caroline State University, 2002, pp 51.
- [7] CML method, 2001. Guinée, J.B.; Gorée, M.; Heijungs, R.; Huppes, G.; Kleijn, R.; Koning, A. de; Oers, L. van; Wegener Sleswijk, A.; Suh, S.; Udo de Haes, H.A.; Bruijn, H. de; Duin, R. van; Huijbregts, M.A.J. Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background. Kluwer Academic Publishers, ISBN 1-4020-0228-9, Dordrecht, 2002, 692 pp

7. Dissemination of results

List of publications from the GREENBAS project.

7.1 Innovation Center Iceland

B. Johannesson og T.I. Sigfusson. Blátrefjar (in Icelandic). Fréttabréf Steinsteypufélags Íslands, 28. árgangur, 1 tbl, bls. 12–13, Febrúar 2015.

7.2 Reykjavik University

Articles and conference papers

Andri Gunnarsson, Eythor Rafn Thorhallsson, Jonas Thor Snaebjornsson. Simulation of experimental research of concrete beams prestressed with bfrp tendons, Nordic concrete research symposium 2014, Reykjavik. Vodskov: 2014, p. 153–156

Eythor Thorhallsson, Todor Zhelyazov, Andri Gunnarsson and Jonas Thor Snaebjornsson. Concrete beams reinforced with prestressed basalt bars. fib Symposium. Concrete – Innovation and Design, Copenhagen, Denmark 18th – 20th May 2015.

Todor Zhelyazov, Eythor Thorhallsson and Jonas Thor Snaebjornsson Simulation of experimental research on strengthening concrete columns by basalt fibre sheets fib Symposium. Concrete – Innovation and Design, Copenhagen, Denmark 18th – 20th May 2015.

Kamal Azrague, Marianne Rose Inman, Lisbeth-Ingrid Alnæs, Reidun Dahl Schlanbusch, Birgir Jóhannesson, Thorsteinn Ingi Sigfusson, Eythor Rafn Thorhallsson, Hjalti Franzson, Arni B Arnason, Sirje Vares: "Life Cycle Assessment as a tool for resource optimisation of continuous basalt fibre production in Iceland" in "Life Cycle Assessment and Other Assessment Tools for Waste Management and Resource Optimization", Professor Umberto Arena, Second University of Naples, Italy Professor Thomas Astrup, Denmark Technical University, Denmark Professor Paola Lettieri, University College London, United Kingdom Eds, ECI Symposium Series, (2016). http://dc.engconfintl.org/lca_waste/10.

Eythor Rafn Thorhallsson, Jónas Thór Snaebjornsson: Basalt Fibres as New Material for Reinforcement and Confinement of Concrete. Solid State Phenomena 04/2016; 249.
DOI:10.4028/www.scientific.net/SSP.249.79

Eythor R Thorhallsson and Jón Ó Erlendsson. Continuous Basalt Fibre as Reinforcement Material in Polyester Resin. In proceedings of 2nd International conference on Mechanics of Composites, Porto 2016.

- Eythor Rafn Thorhallsson, Guðmundur Ingi Hinriksson and Jonas Thor Snæbjörnsson: Strength and stiffness of glulam beams reinforced with glass and basalt fibres. Accepted for publication in Journal of Composites Part B.
- Marianne Inman, Eythor Rafn Thorhallsson, Kamal Azrague. A mechanical and environmental assessment of basalt fibre reinforced polymer (BFRP) rebar and steel rebar in concrete beams. Accepted for publication in Energy Procedia
- Iveta Nováková, Eythor Thorhallsson, Ólafur Wallevik, Lenka Bodnárová: influence of porosity of basalt aggregates on fire resistance and freeze-thaw durability of fibre reinforced concrete. Will be in proceedings of 11th HPC and the 2nd CIC in Tromsø in March 2017

Posters

- Andri Gunnarsson, Eythor Rafn Thorhallsson and Jónas Þór Snæbjörnsson: Bearing capacity of prestressed BFRP reinforced concrete beams Experimental testing & Finite element simulations. COST meeting Kaiserslautern 2014
- Eythor. R. Thorhallsson, Haraldur Audunsson, Jonas Thor Snæbjörnsson, basalt fibre bars as reinforcement for concrete, NordMin workshop, On- and Offshore Exploration and Prospecting in Extreme Nordic Environments. Challenges and Benefits of Finding Exploitable Raw Materials. Reykjavik 23–24 Mars 2015
- Todor Zhelyazov, Eythor Thorhallsson and Jónas Snæbjörnsson. (2015). The mechanical response of Basalt Fibre Reinforced Polymer external reinforcement of cylindrical concrete elements loaded in compression. Cost Action TU1207 meeting in Lecce, Italy 19–21 May 2015.
- Iveta Nováková, Eythor Thorhallsson, Application of Basalt fibres for an enhancement of fire resistance and freeze-thaw durability, COST Action TU1207 meeting in Prague, 2–4 November, 2016

Theses

- Benedikt Rafnsson, Blápráðaframléiðsla á Íslandi. BSc thesis (in Icelandic) Reykjavik University, 2014
- Guðmundur I. Hinriksson, Glulam beams strengthened with pre-stressed basalt fibres, Reykjavik University (2016) MSc Thesis
- Sigurður Halldór Örnólfsson; Yfirborðsmeðhöndlun asfaltbundinna slitlaga, BSc thesis (in Icelandic) Reykjavik University, 2016
- Stefán Ingi Björnsson; Steypt útveggjaglæðning með basaltbendingu, BSc thesis (in Icelandic) Reykjavik University, 2016
- Guðmundur Úlfar Gíslason; Veðurkápa á forsteyptum útveggjaeiningum með basalttrefjabendingu, BSc thesis (in Icelandic) Reykjavik University, 2016

JEI

- Arni B Arnason, Hekla Pumice, NordMin workshop. On- and Offshore Exploration and Prospecting in Extreme Nordic Environments. Challenges and Benefits of Finding Exploitable Raw Materials. Reykjavik 23–24 Mars 2015

Industrial supervision on a B.Sc. thesis:

Benedikt Rafnsson, Blápráðaframléiðsla á Íslandi. B.Sc thesis (in Icelandic) Reykjavik University, 2014.

SINTEF

An abstract titled (see below): "Life Cycle Assessment as a Tool for Resource Optimisation of Continuous Basalt Fibre Production in Iceland" has been accepted and presented at the ECI conference, Life Cycle Assessment and Other Assessment Tools for Waste Management and Resource Optimization, held June 5–10, 2016 at Cetraro (Calabria), Italy.

A conference paper entitled: "A Mechanical and Environmental Assessment and Comparison of Basalt Fibre Reinforced Polymer (BFRP) Rebar and Steel Rebar In Concrete Beams" has been accepted and presented at Sustainability in Energy and Buildings, SEB-16, held in Turin, Italy 11–13 September 2016.

The following scientific journal article has been accepted for publication in Energy Procedia: Inman, M., Thorhallsson, E. R., Azrague, K. (forthcoming). A Mechanical and Environmental Assessment and Comparison of Basalt Fibre Reinforced Polymer (BFRP) Rebar and Steel Rebar in Concrete Beams. Energy Procedia. ISSN: 1876–6102.

SINTEF has prepared a scientific article draft on the Icelandic versus Russian production processes for CBF in terms of their environmental impact.

SINTEF has also prepared a status report and final report to NordMin. Furthermore, SINTEF has contributed to a joint paper with the other GREENBAS project partners that summarizes the findings of the research project.

8. GREENBAS General Conclusions

The main objectives of the GREENBAS project have been accomplished. The only significant exception is that it took longer than expected to find locations with suitable basalt composition. Accordingly, the project did not reach the stage of mining basalt in large quantities. Consequently, the involvement of JEI was less than anticipated. JEI, however, played an active role in the project and provided a significant contribution to its success.

The following is a list of the work packages, deliverables and milestones set up at the start of the project and how the aim was realised.

8.1 Work Package 1. Mining and production

- Deliverable:
 - Database of mines according to desired fibre properties.
 - List of mine related resources fulfilling e.g. viscosity in production and mechanical properties of fibres. December 2015.
- Milestone:
 - Database for material properties relating to extrusion.
 - Material ready for production of prototype fibres. December 2015.

Deliverables 1 and 2 achieved.

Milestone 1 reached. Milestone 2 about to be reached. Experiments are being carried out by Lipex Corporation to fully evaluate suitability of selected locations for fibre production. Database created on the 154 different tested sites.

8.2 Work Package 2. Sustainable use of energy and resources

- Deliverable: Recommended core design of fibre extrusion plant.
- Milestone: Plan for prototype plant using electrical heating. December 2015.

Deliverable achieved after discussions with Lipex Corporation and other specialists.
Milestone reached. Electrical heating of furnaces is a relevant option today.

8.3 Work Package 3. Life Cycle Analysis and sources of raw materials

- Deliverable: Comparison of available resources from Nordic mines and additional Nordic sources considering the life cycle resource efficiency.
- Milestone: Overview of Nordic sources for production of basalt fibres.

Deliverable achieved.
Milestone reached.

8.4 Work Package 4. Production of basalt fibre bars – Choice of mines for concrete products

- Deliverable: Comparison of mines in order to suggest desired end-use of fibres.
- Milestone: Optimal mines identified. December 2015.
- Deliverable: Research in the project showed how basalt fibres can be used in the construction industry. Six papers were published (see the dissemination of results).

Milestone reached (see WP1).

8.5 Work Package 5. CBF as green reinforcement in polyester resin

- Deliverable: List of mines fulfilling optimisation of fibres for a number of end products.
- Milestone: Laboratory scale lamp-post prototypes based on extruded fibres from local mines (High risk element).

Deliverable: Instead of focusing on lamp-posts, research was carried out on the application of basalt fibre mats for strengthening of gluelam beams and laminate plates. Two papers were published (see the dissemination of results).
Milestone reached, but basalt fibres from Russia were used.

Sammendrag

Greenbas prosjektet har fått støtte fra *NordMin*. Prosjektet handler om gjennomførbarheten av produksjon av basalt fiber fra basaltic lava utvunnet på Island. Tre nordiske land er involvert i prosjektet, og har som formålet å utvikle den Nordiske gruvedrift- og mineralindustrien i en bærekraftig måte for økt konkurranse og vekst.

Geologiske undersøkelser fra *Iceland Geosurvey* har ført til kunnskap om hvor man kan finne egnet råmaterialer. Forskning fra *Innovation Centre Iceland (ICI)* har ført til en undersøkelse av 154 potensielle utvinningsområder i Island, og en skjerpet definisjon av forholdene for kjemiske sammensetning av utvunnet basalt malm. I tillegg har ICI analysert forretningsmodeller for en oppstart basalt fiber fabrikk i Island. Engasjement fra Islandske gruveselskapet, *JEI*, har sikret industriell relevans, mens bidraget fra *University of Reykjavik* har ført til økt forståelse for bruk av basalt fiber i ulike byggematerialer i en Islandske kontekst. Engasjement fra eksperter fra både *SINTEF* i Norge og *VTT* i Finland har vært avgjørende for dette prosjektet. *SINTEF* har brukt livssyklusanalyse for å vurdere hele livsløpet av basalt fiber som et produkt i et miljømessig perspektiv, mens *VTT* har sett på behovet og gjennomførbarheten av supplerende materialer i produksjonsfasen for å forbedre den kjemiske sammensetning av basalt.

På bakgrunn av dette er det nå mulig å starte en ny fase; nemlig, en serie av forberedelser og prøver for å etablere en ny basalt fiber produksjonslinje i Island.

Nordic Council of Ministers
Ved Stranden 18
DK-1061 Copenhagen K
www.norden.org

GREENBAS

The GREENBAS project is about the feasibility of producing continuous basalt fibres from Icelandic basalt. The project was made possible with support from NordMin, with the aim to develop the Nordic mining and mineral industry.

Geological investigations by Iceland Geosurvey have resulted in insight into locations of the most ideal materials. Work at Innovation Centre Iceland (ICI) led to the definition of the basalt properties required. ICI also analysed the business conditions for a start-up factory. The involvement of JEI has ensured industrial relevance in tandem with the contribution of the University of Reykjavik team in gaining an understanding of the importance of applications in building materials.

The involvement of SINTEF Norway and VTT Finland was crucial. They provided their expertise to analyse the life-cycle of basalt fibres and the feasibility and need of artificial external components.

On basis of this project, a new phase can be started: the preparations for establishing a continuous basal fibre factory in Iceland.