ALIGNMENT OF STEEL FIBRES USING HELMHOLTZ COIL

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ABSTRAKT

Tento článek popisuje návrh a výrobu dvou Helmholtzových cívek, které byly použity pro orientaci drátků v čerstvé betonové směsi. V článku jsou popsány dlouhodobé cíle výzkumu spojeného s orientací drátků pomocí generovaného magnetického pole. Je zde uvedena směs použitá při zarovnání drátků pomocí magnetické pole cívky. Magnetické pole cívky je podrobně popsáno pomocí modelu vytvořeného v softwaru FEMM 4.1 a jsou zde uvedeny jeho klíčové parametry. Je zde popsána metodologie pro zkoumaní pohybu jednoho osamělého drátku během procesu orientace a jsou zde uvedeny výsledky experimentu vykonaného na základě uvedené metodologie. Z dosavadních výsledků je zřejmé, že navržená a sestavená Helmholtzova cívka je schopna zarovnávat drátky v čerstvé betonové směsi a orientovat je s isoliniemi magnetického pole cívky. Všechny návrhové parametry cívky jsou uvedeny. Pohyby drátků během zarovnání byly měřeny a vyhodnoceny. Svislý pokles drátků si nelze jednoznačně spojit s jejich vystavením magnetickému poli vzhledem k charakteru dosavadních experimentů.

KLÍČOVÁ SLOVA

Orientace drátků • Cementový komposit • Magnetické pole • Automatizace

ABSTRACT

This article focuses on design and manufacturing of Helmholtz coils used for aligning the steel fibres in fresh concrete mixture for creating the Aligned Steel Fibre Reinforced Concrete (ASFRC).Long term goals of research and also the SCC mixture used for aligning the fibres in magnetic field generated by Helmholtz coil are described. Methodology of first experiments is presented. Early experiments were focused on examination of behaviour of single steel fibre in fresh concrete mixture exposed to magnetic field. Parameters of used coil and generated magnetic field are described with finite element model of Helmholtz coil. Movement of fibres during the alignment process is described and based on measured data. Manufactured Helmholtz coil is suitable for alignment of MasterFibre 482 fibres (steel fibres) in fresh concrete. The vertical movement is also measured and data are presented. The connection of vertical movement and alignment was not directly clarified with current experiment setup.

KEYWORDS

Fibre Orientation • • Cementitious Composite • Magnetic Field • Automation

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1. INTRODUCTION

Concrete is brittle material with high compressive strength and low tensile strength. Tensile strength is traditionally transferred to common steel reinforcement bars or the structural object is prestressed and the tensile stresses are reduced in general. These methods are well handled nowadays, but could be costly and time consuming for structures with shape complexity and do not provide solution for additional cracking propagation which can result in reduced life-time of the structure. Various types of fibres is offered and used for the reduction of cracking and they are used for their tensile load-bearing capacity as well. Efficiency of fibres depends on their material characteristic, shape and fibre distribution in the structural element and the trajectory of stresses underneath is load-bearing member usually exposed. Aligned fibres according to specific loading stresses can positively affect the tensile behaviour of cement composite, ductility and after-cracking hardening of specimen (Abrishambaf et al. 2017), (Mudabu et al. 2018). FRC also is giving the ability to overcome limitations of common steel reinforcement and allows to use full the potential of concrete to be casted in various shapes of formworks. This potential could be used firstly for precasted concrete members where shape now can be optimized for loads which is members exposed during his life cycle.

2. MANUFACTURING AND RESEARCH

Long term goals of research alignment of steel fibres with magnetic field are following:

- What is the impact of different voltage time-dependencies on steel fibres orientation and distribution?
- What are the key fresh concrete properties needed for determining the proper voltage time- dependency employing soft computing? How to measure these properties effectively in a very short time before casting?
- What are the most suitable soft computing models to reveal the hidden patterns in the collected data?

2.1. Fresh Concrete Properties

Based on literature, the fresh concrete properties are crucial for determining the strength of magnetic field necessary for alignment of steel fibres in ASFRC (Villar et al. 2019). The goal was to design the sufficient SCC mixture (Table 1, Figure 1 b) for aligning the steel fibres and to determine the in-situ small scale test of fresh concrete which allows to determine easily the ideal strength of magnetic field used afterwards for the alignment.

Table 1: *SCC mixture design*

Materials	Composition [kg m^{-3}]
CEM 42.5 R	535.1
Fine Aggregate	375.6
Limestone	267.6
Sand	995.3
Water	155.2
Super-plasticizer	37.5
Steel Fibres	134.8

For the fast testing of fresh mixture of SFRC was a small scale slump test design. (Figure 1 a)

a) b)

Figure 1: *a) 3D printed slump test cone b) SFRC sample .*

2.2. Design of 1st Helmholtz Coil

As proof of concept, there was designed small Helmholtz coil where the single fibre (MasterFibre 482) in silica oil was successfully oriented according to magnetic field isolines. The Helmholtz coil prototype is composed of two coils connected in series or in parallel regime. The advantage of this set up is that the tested sample is visible and accessible through time the whole experiment is held .The coil was designed based on equation for magnetic induction. (Equation 1) This approach was successfully applied by Mu (Mu & et al. 2019), Wijffels (Wijffles & et al. 2017) and Takáčová (Takáčová 2020).

$$B = \mu_0 \times I \times \left(\frac{4}{5}\right)^{\frac{3}{2}} \times \frac{z}{r} \tag{1}$$

Where B is magnetic induction of coil and for the testing setting was B = 20 mT in the homogeneous part of magnetic field. μ_0 is permeability of vacuum. I is electric current going through the coils which was for the designed geometry, used wire and power supply set I = 2.4 A. Power supply maximum voltage was 48.0 V. The coated copper wire used has diameter d_{wire} = 0.5 mm and number of wounds was z = 570 times on each of coils. Inner diameter of coil was set to d_{coil} = 120 mm. Distance between coils should be equal to the inner radius of coil and was set to z = 60.0 mm.

2.3. Design of 2nd Helmholtz Coil

First coil with magnetic induction of B = 20 mT was not sufficient for aligning steel fibres in fresh concrete mixture such as is the one presented in (Table 1). It was necessary to design coil with stronger magnetic field. Wijffels et al. (Wijffles & et al. 2017) used coil generating magnetic induction of B = 60 mT and were successful with aligning the steel fibres Dramix 3D, 4D and 5D in SCC mixtures. Hajforoush (Hajforoush et al. 2020) used in his research coil with B = 50 mT for successful alignment.

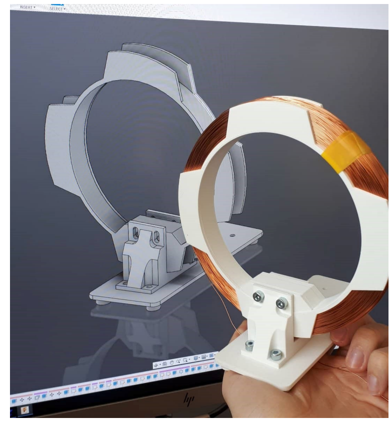

Figure 2: *The first designed and produced Helmholtz coil.*

For dimensions and properties of more robust Helmholtz coil was used (Equation 1) with expected B = 56 mT in between the coils in homogeneous part of magnetic field. Parameters were following.The coated copper wire used has diameter d_{wire} = 1.4 mm and number of wounds was z = 490 rounds on each of coils. Inner diameter of coil was set to d_{coil} = 120 mm. Distance between coils was set to z = 60.0 mm. Power source was used same as for designed coil with maximum voltage was 48.0 V and direct current provided I = 9.55 A. The validity of calculated magnetic induction was clarified with modeling the coil in FEM software for design of electromagnetic devices FEMM 4.2 (Figure 3) and also with in-situ measurements after manufacturing.

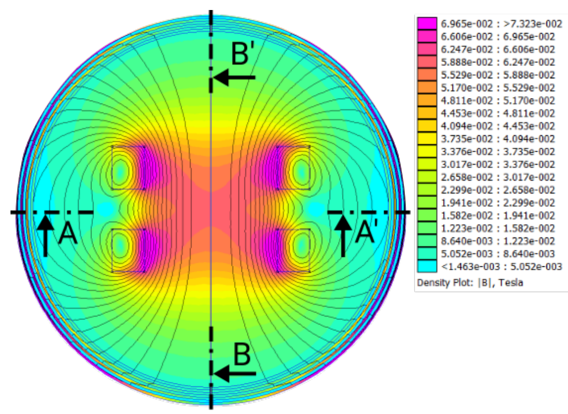

Figure 3: *Magnetic induction B modeled in FEMM 4.2.*

Magnetic field is considered as homogeneous in inner part of coil which is presented in the section A-A' (Figure 4). As can be seen, the homogeneous magnetic field is consistent in inner space of designed coil and maximal magnetic induction B = 59 mT which corresponds with calculated value in early design stage of project. Magnetic induction goes down rapidly after exceeding the position of coils. From longitudinal section B-B' (Figure 5) is obvious that homogeneous magnetic field could be considered in 2/3 of future specimens. Length of proposed specimens is l = 160mm. Maximal magnetic induction B = 59 mT. It is obvious from the graph that magnetic induction goes down rapidly after exceeding the position of coils (distance -50mm and +50mm). Position "0" on horizontal axes is defined by centre of gravity of both sections thought designed Helmholtz coil.

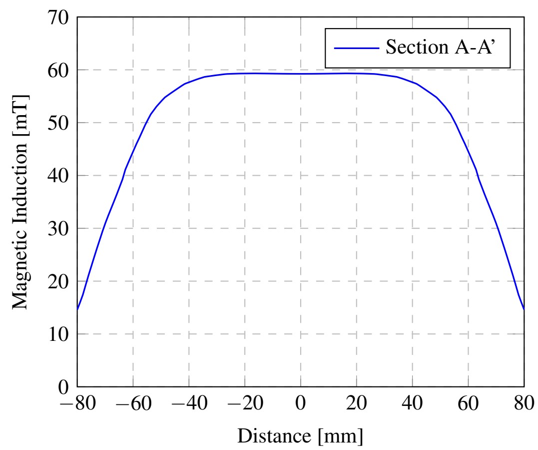

Figure 4: *Cross-section of magnetic field A-A'*

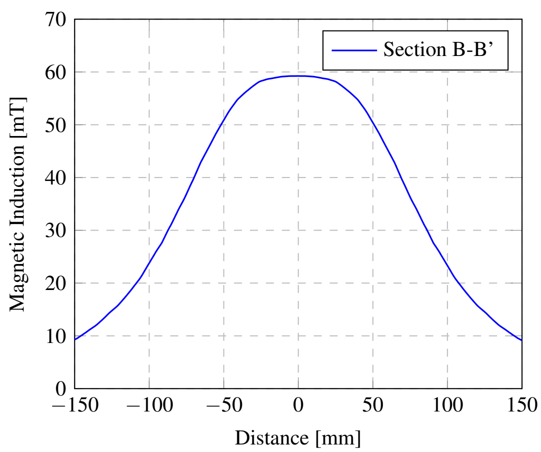

Figure 5: *Longitudinal section of magnetic field B-B'*

Coil was manufactured after evaluation of properties with usage of CNC milling of plastic plates used for construction of coil sites and also of MDF plate used for base holder of both coils securing the stability of the device. Additive manufacturing technology of 3D PLA plastic printing was used for centre cylinders of both sub-coils and also for spacer securing the correct position after assembly of device. After that coils were connected to power source in parallel order and were equipped with switch button. Cables are driven through the base of the Helmholtz coil for better manipulation and also for safety of device operator. Device is described on Figure 6.

3. METHODS

Considering available data from literature, we are going to collect our own data, based on experiments to ensure the validity. Multiple fresh concrete mixtures are going to be tested for orientation of steel fibres under variable effects of magnetic fields. Data related to the rheological properties of fresh concrete mixtures with steel fibres are going to be collected as well. The oriented samples of ASFRC specimens are going to be evaluated with destructive bending tests and the position (orientation) of steel fibre in ASFRC is going to evaluated with image processing. Collected data are going to be used for design of soft-computing methods. Methods of

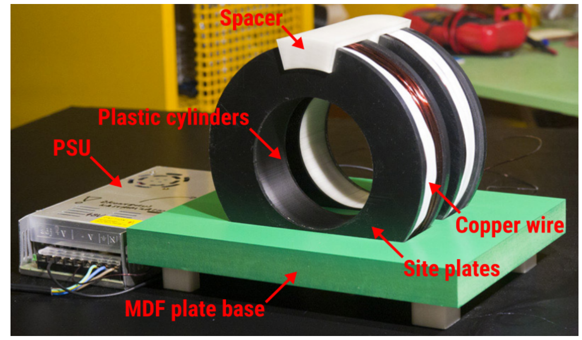

Figure 6: *Assembled coil after manufacturing with description.*

Table 2: *MasterFibre 482 properties*

Material	Brass Coated Steel
Manufacturing	Monofil
Diameter	0.20 mm
Lenght	13 mm
Lenght / Diameter	65
Ultimate tensile Streght	2200 MPa
Water Absorbtion	Low
Alkali Resistance	High

soft computing operates with the levels of uncertainty, therefore there are appropriate for this type of research, where many factors are taken into account. Afterward, there is going to be prepared relation between mixture properties, fibre orientation a magnetic field used for alignment of fibres. Therefore we are going to be able predict the fibres orientation and the strength properties of designed ASFRC samples which is crucial for design process.

3.1. Single fibre behavior in magnetic field

First we focused on single fibre behaviour in fresh concrete exposed to magnetic field with maximum magnetic induction $B = 59$ mT. Steel fibre "BASF MasterFibre 482" with the following properties was chosen for single-fibre experiment Table 2.

Setting for experiment was following. Concrete mixture with single fibre was poured into the mould, position of fibre in concrete was recorded. Then specimen was placed into the inner space of coil and exposed to magnetic field generated by current circulating in coil for defined amount of time. After that were position of fibre measured once again and these results compared.

Designed formworks are cuboid shape and consists of two separate peaces for easier demoulding after measurements are done. Formworks were 3D printed with inner dimensions of 84mm x 54 mm x 32 mm. Outer dimension was limited with diameter of Helmholtz coil where these formworks were put in for alignment of steel fibres.

Concrete mixture (Table 1) was filled approximately into the half of full height of the formwork, then single fibre was placed on the surface of fresh concrete in the centre of formwork, perpendicular to isolines of magnetic field. That means that successful alignment of the fibre would be occurred in case of 90° rotation. When the fibre change orientation to parallel with isolines of magnetic field. Specimen with fibre was photographed perpendicularly to the plane of concrete surface and depth of fibre was measured (z coordinate) on both ends of steel fibre. After that, second layer of concrete was poured and fibre was fully covered in fresh concrete. When second layer of concrete was placed, there was expected small movement even without the alignment as described by (Mudabu et al. 2018), (Huang et al. 2018) and (Švec et al. 2014). Formwork was placed inside the coil (Picture 7.). When specimen was placed inside, coil was turned on and fibre was exposed to magnetic field in 3 time sections, duration of each was 10 s. Formwork and the setting up phase of experiment before pouring second layer of concrete also with relation to isolines of exposed magnetic field can be seen on picture 8.

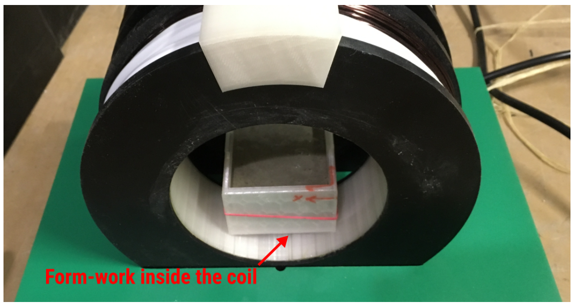

Figure 7: *Formwork with fibre fully covered in concrete in the coil during alignment.*

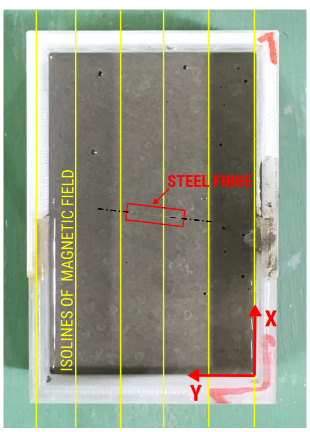

Figure 8: *Steel fibre placed on the layer of fresh concrete.*

When the alignment process was completed, the samples were laid to rest approximately for 4-6 hours. The concrete matrix was still weak, then revealing the fibre take place. The upper layers of concrete were gently removed until the fibre was fully revealed. Than pictures was taken and depth measured for future data assessments. After revealing each fibre, it was clear that fibre alignment was successful as presented on picture 9. Then picture of revealed fibre was taken again and also depth was measured on both ends of steel fibre. samples were tested with single fibre and also sample with two fibres with distance of 2 cm. Fibres did not affected each other for this distance. So they were considered as two separate samples.

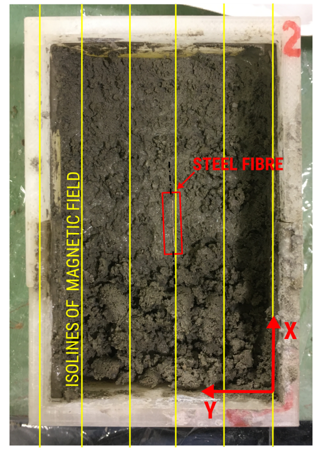

Figure 9: *Steel fibre after alignment, revealed.*

4. EVALUATION

As mentioned above each fibre position was measured before and after alignment process. The z coordinate (depth) was measured manually. For coordinates x and y in plane of surface of first layer of fresh concrete was used image analysis. All samples were exposed to homogeneous magnetic field for 3x10s with 10s pause between turning the coil on again. Similar approach was used by Villar (Villar et al. 2019). Samples without the exposure to the magnetic field were also tested for validating mainly the change of vertical coordinates. Collected data was turn into 3D models (Picture 10) with visualization of movement vectors (yellow) and comparing the beginning (red) and end position (blue) of steel fibre. There was done in total 13 experiments so far and exposed to magnetic field was 11 samples in total.

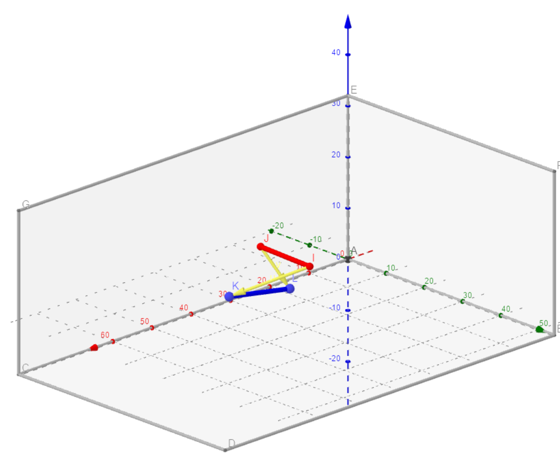

Figure 10: *3D representation of experiment .*

Fibres alignment and their movement in plane is presented in picture (11). The original position is presented with red and the position measured after alignment is blue. Samples 2 and 3 was not exposed to magnetic field. Movement for samples 2 and 3 is caused by pouring the second layer of fresh mixture, pushing the fibre in direction of mixture flow described by (Švec et al. 2014). For sample 4 there was an error during revelation of fibre which caused incorrect fibre positioning after alignment process. Samples 1, 9 and 10 show higher in plane movements than the other samples. Samples 5, 6, 7, 8, 11, 12 and 13 show the successful alignment.

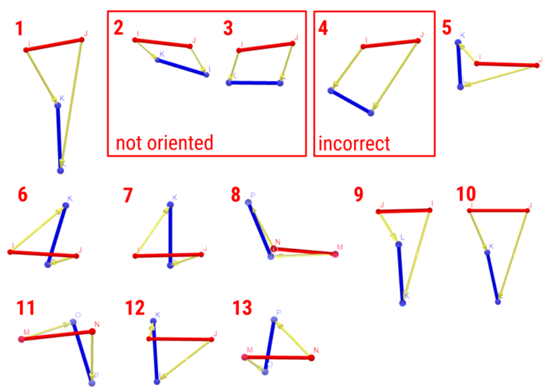

Figure 11: *2D representation of experiment.*

Total movement of beginning and end node of steel fibre is described in Table 3 including the z movement which is important attribute. Z movement is presented for exposed and also for not exposed samples. Z movement is presented mainly because of setting of experiment. Second layer of concrete press the fibres down into the first layer and this phenomenon is associated with drowning. Drowning itself needs to be tested separately, without layering of concrete. Maximal movement of fibres ends is between 5.06 mm and 27.53 mm. Maximum movement was measured for sample 1 and in comparison with movement of non-exposed samples 2 and 3 it is clear, that movement is affected by magnetic field.

5. DISCUSSION

Based on data published above it is clear that coil is suitable for casting ASFRC samples. Fibres during experiments were successfully aligned with magnetic filed isolines and fibres movement was measured.

The future work is going to be focused on exploration of behaviour of multiple fibres presented in samples and on evaluation of load bearing capacity of the aligned and non aligned samples. Experiments are going to include the hybrid fibre reinforcement where are used magnetic and non magnetic responding fibres. This combination of MasterFibre 401 and MasterFibre 482 should increase the load bearing capacity of specimens and also did not eliminate the advantages of randomly oriented fibres in the specimen. The collected data are going to be used for soft computing methods design used for determination of load bearing capacity of the sample before casting based on the magnetic field parameters, amount and type of fibre used and the rheological properties of concrete.

Table 3: *Movement of fibres*

Sample	Node	u_x [*mm*]	u_y [*mm*]	u_z [*mm*]	u_{tot} [*mm*]
1	Begining	-10.57	-5.90	-11.68	16.82
	End	-24.74	4.27	-11.30	27.53
2	Begining	-4.47	-5.15	-9.72	11.87
	End	-6.39	-3.80	-7.15	10.31
3	Begining	-8.41	2.70	-9.67	13.10
	End	-10.62	3.49	-6.57	12.97
4	Begining	-9.83	7.02	-8.09	14.54
	End	-16.15	10.29	-10.09	21.65
5	Begining	4.35	4.01	-8.00	9.95
	End	-4.77	15.94	-8.50	18.68
6	Begining	9.60	-11.20	-6.40	16.08
	End	-2.21	5.79	-7.10	9.42
7	Begining	9.73	-6.67	-8.50	14.54
	End	-2.06	5.86	-8.50	10.53
8	Begining	19.70	-5.86	1.80	20.63
	End	7.02	4.26	-1.10	8.28
9	Begining	0.42	-13.69	1.10	13.74
	End	-9.87	-5.37	-1.30	11.31
10	Begining	-9.23	-4.12	-8.70	13.34
	End	-20.35	6.27	-10.20	23.61
11	Begining	3.49	-10.02	-9.50	14.24
	End	-10.07	-0.08	-8.60	13.24
12	Begining	3.46	-0.82	-3.60	5.06
	End	-8.38	10.71	-5.80	14.78
13	Begining	-2.62	-3.78	-5.90	7.48
	End	6.88	6.93	-6.40	11.68

6. CONCLUSION

In this article, project of aligning the steel fibres in general and also in detail for his early stage is described. Designs of two Helmholtz coils are presented. First coil prototype is used as proof of concept of an idea based on previously reviewed literature. Second coil prototype is used for actual research purposes. Geometry of both coils are described and all crucial parameters about power supply and generated magnetic field are presented. Concrete mixture design used for alignment of steel fibres in magnetic field is provided. Methodology is described for clarification coils abilities for aligning the fibres with their magnetic field. Results of single fibre alignment experiments are published with detailed overview of fibres movement. At the end of the article, future work and goals are defined.

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