ALIGNMENT OF STEEL FIBRES WITH ELECTROMAGNETIC FIELD

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ABSTRAKT

Tento článek popisuje vliv orientace ocelové rozptýlené výztuže v betonových prvcích na jejich finální únosnost a na tvar jejich pracovního diagramu. K orientaci ferromagnetických drátků je užito působení generovaného magnetického pole a v článku je uvedeno několik příkladů úspěšné aplikace magnetického pole pro usměrnění drátků v čerstvé betonové směsi včetně specifikace magnetického pole, parametrů cívky a způsobu jakým byl prvek působení magnetického pole vystaven. V článku jsou uvedeny možnosti následného hodnocení úspěšnosti zarovnání drátků a jsou uvedeny metody jakými zarovnání lze hodnotit (rentgen, analýza obrazu atd.) Dále je představen vlastní výzkum, kde je prezentován návrh Helmholztovi cívky a návrh směsi, která bude využita pro další experimenty. Po vyhodnocení dat je představen záměr o vývoj predikční metody za užití soft-computingu.

KLÍČOVÁ SLOVA

Orientace drátků • Cementový komposit • Magnetické pole • Automatizace

ABSTRACT

This article describes the possible approaches for aligning the ferromagnetic fibre reinforcement in fresh concrete mixture and the affect of aligned fibres in Aligned Steel Fibre Reinforced Concrete (ASFRC) on the final strength and the working diagrams of such samples. For the fibres alignment is generated magnetic field used. In the article, there are presented examples from literature, where the successful aligning of steel fibres was used. Described are the experiments set ups under effect of homogeneous magnetic field, impulse of magnetic field and linear movement of fresh sample through the magnetic field. There are also presented methodologies how to evaluate the alignment (X-ray, image processing etc.). There is mentioned the following research, first Helmholtz coil design and mixture design for aligning the fibres. The development of prediction method based of soft-computing of alignment of steel fibres is described.

KEYWORDS

Fibre Orientation • • Cementitious Composite • Magnetic Field • Automation

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 now days, 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 they 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. Orientation of steel fibres in Steel Fibre Reinforced Concrete (SFRC) is done via several approaches. This article is focused on method where electromagnetic field is used.

2. STATE OF THE ART

Methods described in literature used for aligning the steel fibres in SFRC are divided into to two main categories. The first is passive aligning of fibres in fresh concrete mixture. Passive aligning of fibres is done via setting the casting of concrete specimen and the casting itself (Mudabu et al. 2018). It is defined with flow of mixture and movement trajectory of concreting hose. This behaviour was described, modeled and tested by (Švec et al. 2014) where for oriented fibres was crack-opening stress twice higher than for not aligned specimens. Other phenomenon, effect of form-work and geometrical shape of mouth of concreting hose, is described by (Huang et al. 2018).

The other approach is active and is determined by usage of outer forces (generated magnetic field or fields) for aligning the fibers in fresh concrete. The field of interest of this article is held in this sphere. Ferromagnetic fibres in SFRC are affected by the magnetic forces and by the bi-pole behaviour. The fibres are externally forced to aligning with the magnetic field silo-lines. The possitive effect of tensile behaviour is proven by many research groups. Ru Mu, et al. in (Mu & et al. 2019) observed the 51% increase of ultimate tensile strength of specimen in ASFRC compared to not aligned, randomly distributed fibre in SFRC. Wijffel M. J. H., et al. in (Wijffles & et al. 2017) observed also higher ultimate tensile strength and higher energy absorption capacity of ASFRC tested specimen. Also was observed the dipole-dipole behaviour related to strength of magnetic field used for alignment of steel fibres, where fibres affected one each other. That could result in linear clustering and "ropes" of fibres.

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2.1. Specimen in Constant Magnetic Field

Hajforoush et al. (Hajforoush et al. 2020) designed the coil generating magnetic field with intensity |B|= 0.5 T. Coil (Figure 1) was made by PVC cylinder with diameter 200 mm and was wound up with coated copper wire with with the diameter 1.35 mm with total of 1100 turns. Dimensions of the coil needs to fitted to dimensions of tested specimens where the homogeneous magnetic field is considered in 70% length of coil. For heat reduction, due to electric current passing was set to 7 A, pressman sheets were placed among the wire rounds. The SCC concrete mixture was design with dose of 1.5% of steel fibres. (Hajforoush et al. 2020)

Results observed with 3-point bending test on samples with dimensions 70 x 70 x 280 mm^3. The increase in residual flexural strength of aligned samples up to 161.45% compared to samples with not aligned fibres. The mid span deflection was increased for ASFRC up to 127.52% compared to not aligned SFRC samples. (Hajforoush et al. 2020)

Figure 1: *Experiment setting (.png file (Hajforoush et al. 2020)).*

The homogeneous magnetic field was also experimentally tested by the research of Abrishamba et al. where was designed U-shaped electromagnet and specimens of ASFRC and SFRC was casted. Prismatic specimens was 430 x 40 x 30 mm^3 where for dose of 3.0% steel fibres are presented results on Figure 2. Where the concreted specimens where tested in uni-axial tensile test, where the fibres was oriented according to principal stresses (0°), not-oriented or vertically to principal stresses (90°). There is described significant increase in crack-opening stress, ultimate tensile stress and the hardening tensile branch for well oriented fibres (0°). (Abrishambaf et al. 2017)

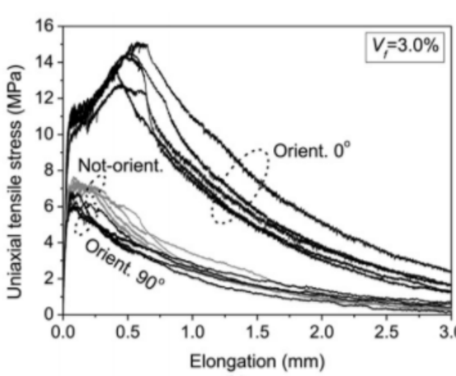

Figure 2: *Uni-axial tensile test - elongation graph (.png file (Abrishambaf et al. 2017).*

2.2. Specimen in Sequences of Magnetic Field

Research team of Villar, et al. experimentally tested pulses of electromagnetic field generated by a coil and presented equation (1) that directly relates induced magnetic torque $\vec{\tau_M}$ with the rotation of steel fibres.

$$\vec{\tau_M} = \vec{\mu_f} \times \vec{B} = \left\|\vec{\mu_f}\right\| \left\|\vec{B}\right\| \sin\Theta\,\hat{u} \qquad (1)$$

Where $\vec{\mu_f}$ is magnetic dipole moment and Θ is the intial orientation angle of fibre related to the induced magnetic field silo-lines. Where $\Theta \approx 0$ represents the ideally aligned steel fibre in cement matrix. Magnetic field generated by a coil is represented with magnetic intensity $\vec{B}$. Therefore fibres with angle near to 45° are exposed to the strongest value of $\vec{\tau_M}$. According to the reaserch of Villar, et al. the magnetic torquoe $\vec{\tau_M}$ has to be higher than the rheological torque which can be measured on the fresh cement mixture in rotational rheometer. (Villar et al. 2019)

The rotation of fibres was initiated by the pulse of the coil controlled by discharging electrical circuit. Values of maximum reached magnetic field are in range from 60.5 mT and 77.8 mT. In results, there is expressed the relation between initial angle of fibre. In total, the biggest change in $\Delta\Theta$ of fibre is for the $\Theta = 90$ and the for the fibre with angle lower than $\Theta = 20$ is the alignment despite the magnetic field strength difficult to achieve. Repetition of magnetic impulses increase the total alignment of fibres but it is also limited by the value of circa $\Theta = 20$. Figure 3. (Villar et al. 2019)

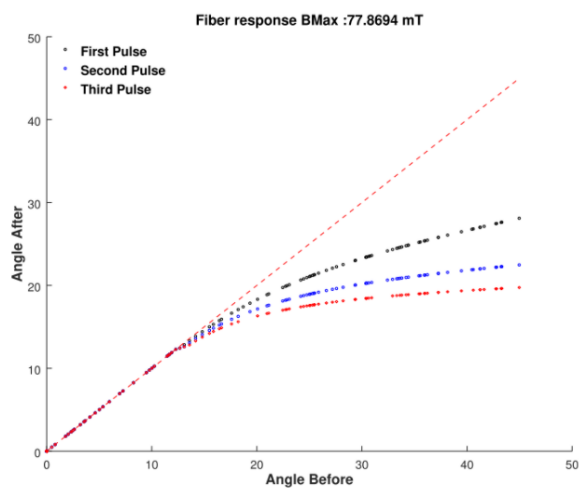

Figure 3: *Convergence of alignment to orientation angle equals 20° for repeated impulses (png. file (Villar et al. 2019)).*

2.3. Motion Specimen Through the Magnetic Field

This approach allows to produce longer ASFRC specimens. Specimen are moved through the coil which is generating the magnetic field and fibres are aligned with silo-lines. This is represent by research of Wijffels et al. (Wijffles & et al. 2017) where solenoid type coil was designed and constructed and samples where exposed to magnetic field for 80 s . Where strength of magnetic field in homogeneous inner part of the coil equals |B|= 60 mT. The following magnetic strength was determined by the ability of rotating the fibres in fresh concrete mixture and by the avoiding the clustering of fibres. Aligned steel fibres (Dramix 3D) with clustering effect in silica oil are shown on Figure 4.

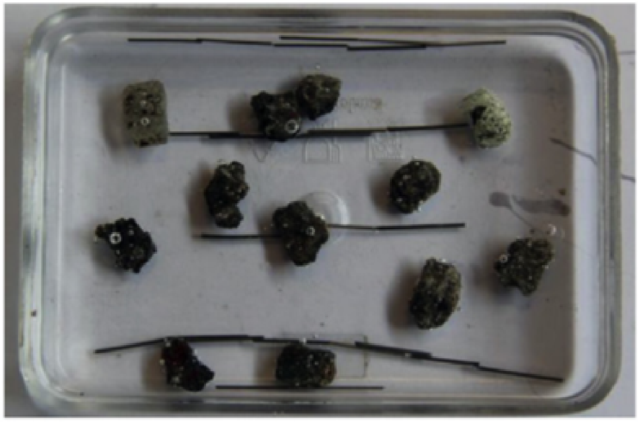

Figure 4: *Aligned fibre with clustering effect (png. file (Wijffles & et al. 2017)).*

For concrete specimens was designed SCC mixture where the rheological properties of fresh concrete was measured. Wijffels, et al. is pointing out that the rheological properties of concrete (μ plastic viscosity and τ yield stress) are significantly changing in time after the proper mixing of concrete mixture. The fresh concrete mixture without fibres were tested in 20 minutes intervals and for μ varies from $26.6\,\mathrm{Pa} \times \mathrm{s}$ s to $39.0\,\mathrm{Pa} \times \mathrm{s}$. For τ varies from 25.1 Pa to 51.9 Pa. The time dependency of these attributes of fresh mixture are directly affecting the optimal strength of magnetic field generated with coil and therefor the proper rotation and soaking the fibres in ASFRC. The experiment was prepared that 90°rotation was desired for optimal position of fibres. The results presented are showing that in case where the alignment of steel fibres was successful, soaking of fibres is observed compared to samples with higher viscosity, where the rotation was not full filled. (Figure 5)

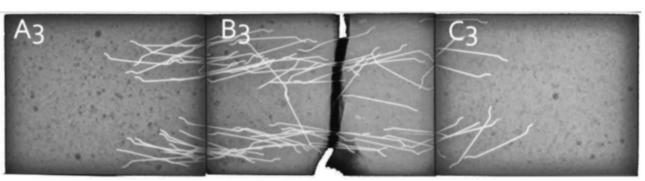

Figure 5: *X-ray shot of bottom third of specimen ASFRC (png. file (Wijffles & et al. 2017)).*

3. RESEARCH POSSIBILITIES

Based on the literature review following goals was set:

- 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?

3.1. 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. The goal was to design the sufficient SCC mixture (Table 1, Figure 6 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. The mixture designed is iterative process and the mixture is going change slightly through the research process.

Table 1: *SCC mixture design*

Materials	Composition [$\mathrm{kg\,m^{-3}}$]
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 [%]	3.0

For the fast testing of fresh mixture of SFRC was a small scale slump test design. (Figure 6 a)

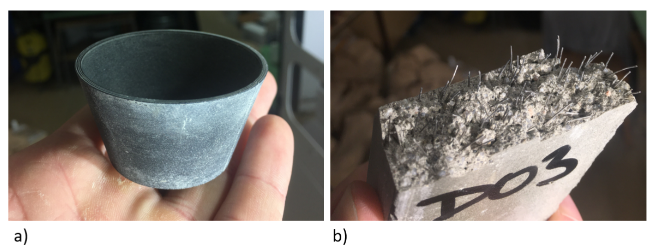

Figure 6: *a) 3D printed slump test cone b) SFRC sample (png. file).*

3.2. Coil and Controlled Magnetic Field

As proof of concept, there was designed small Helmholtz coil where the single fibre (MasterFibre 482) in silica oil was successfully oriented. The Helmholtz coil prototype are in general two coils connected is 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 2)

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

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

For the further research new Helmholtz coil is being designed. The new coil is going to allow testing of bigger specimens and the full control and regulation beneath the current and also allows to generate impulses of magnetic field.

Figure 7: *The first designed and produced Helmholzt coil (png. file).*

3.3. Data collection and evaluation

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 SFRC is going to evaluated with image processing. Collected data are going to be used for the designing soft-computing method. Methods of 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 orientation and strength properties of designed ASFRC samples which is crucial for design process.

4. CONCLUSION

In the article are presented methods of alignment of steel fibres with usage of generated magnetic field on fresh concrete samples and the significant effect on the crack opening strength, ultimate strength and occurring of the tensile hardening branch in the work diagram of tested samples. Successful orientation of steel fibres with generation of magnetic field is presented based on literature review. The various approaches of fibres alignment are presented. Described are methods with the impulses of magnetic fields, homogeneous magnetic field or by motion through the homogeneous magnetic field. Presented are also methodologies for evaluation of fibres alignment of steel fibre in ASFRC like image processing and x-ray shooting of samples. After the literature review there is presented the possibilities for research with involving the own data collection, design of Helmholzt coil which is able to generate the controlled magnetic field, fresh concrete rheological data collecting and designing the soft computing method for ability to predict the ASFRC strength properties.

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