

AN ASSESSMENT OF KEY FACTORS FOR IMPLEMENTING MAGNETIC NDT METHOD ON UHPFRC STRUCTURES

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For my parents
and
my brothers

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RESUMO

Os compósitos cimentícios de ultraelevado desempenho reforçados com fibras (*UHPFRC* na sigla em inglês) tornaram-se recentemente um dos materiais mais eficazes e bem-sucedidos usados na construção civil. Os *UHPFRC* referem-se a uma família de compósitos cimentícios, que contêm uma grande quantidade de fibras curtas de aço curtas. Os *UHPFRCs* demonstram uma melhoria muito significativa em resistência, trabalhabilidade, durabilidade e ductilidade em comparação com os betões reforçados com fibras normais. A resposta à tração dos *UHPFRC* depende fortemente do tipo, conteúdo e distribuição final das fibras em relação à direção das tensões aplicadas. Como resultado, a avaliação *in situ* de suas propriedades, sem a necessidade de extrair carotes, aplicando um método de medição não-destrutivo, representa um feito muito importante. Recentemente, uma equipa de investigadores da Faculdade de Engenharia da Universidade do Porto, Portugal (FEUP) desenvolveu um método de ensaio não-destrutivo baseado nas propriedades magnéticas distintas das fibras metálicas e da matriz cimentícia que constituem o *UHPFRC*.

O método NDT desenvolvido foi baseado nas propriedades magnéticas das fibras de aço, para a deteção *in situ* dos indicadores de conteúdo e orientação das fibras. A sonda magnética projetada é capaz de realizar medições de indutância. Além disso, foram propostos dois indicadores do conteúdo e orientação das fibras, a partir da medição da indutância em duas direções perpendiculares em cada zona do elemento. O desempenho deste método não-destrutivo foi validado em amostras de *UHPFRC* com diferentes composições de matriz, comprimento das fibras, conteúdo das fibras e orientação das fibras.

O presente trabalho centra-se na avaliação de fatores-chave para a implementação da sonda magnética em elementos de *UHPFRC*. Estudou-se a influência da terceira direção nos resultados da medição de indutância, realizando as medições em amostras cúbicas de pequena dimensão. Além disso, para entender o impacto da direção da betonagem e da rugosidade da superfície nos resultados da indutância e, consequentemente, nos indicadores de orientação e teor de fibras. Foram realizados ensaios em pequenas placas betonadas em diferentes direções e com vários tipos de acabamento da superfície. A última campanha experimental, concentrou-se no efeito da espessura dos elementos de *UHPFRC*, tendo-se realizado as medições em provetes cilíndricos espessuras variáveis.

PALAVRAS-CHAVE: compósitos cimentícios de ultraelevado desempenho reforçados com fibras (*UHPFRC*), método não-destrutivo, indutância, conteúdo de fibras, orientação de fibras

ABSTRACT

Ultra high performance fibre reinforced cementitious composite (UHPFRC) has recently become one of the most effective and successful materials being used in construction. UHPFRC refers to a family of cementitious composites, which contains a high amount of short and discrete steel fibres. UHPFRCs demonstrate a very significant improvement in strength, workability, durability and ductility in comparison to the normal reinforced concretes. The tensile response of UHPFRC strongly depends on the type, content and final distribution of the fibres with respect to the direction of the applied stresses. As a result, the “on-site” assessment of its properties, without the need to take core samples, by applying a reliable non-destructive measurement method represents a very important goal. Recently, a team consisting of the experts of the Civil and Electrical Engineering departments of Faculty of Engineering, University of Porto, Portugal (FEUP) developed an NDT (non-destructive) method.

The developed NDT method was based on the magnetic properties of the steel fibres, for the in-situ detection of the fibre content and fibre orientation indicators. The designed magnetic probe was capable of performing inductance measurements. Moreover, the reliable equations of the fibre content and fibre orientation indicators were derived, only by getting the inductance in two perpendicular directions on each zone of the element. The performance of this NDT method has been validated on UHPFRC specimens with different matrix formulations, fibre length, fibre content, and fibre orientation.

The present work focuses on the assessment of key factors in implementing the magnetic probe on UHPFRC elements. It introduces the influence of third direction on inductance measurement results by performing the measurements on small-scale cubic specimens. Furthermore, to understand the impact of casting direction and different surfaces on inductance results and, consequently, fibre content and orientation indicators, an experimental campaign on small plates with different casting directions and various types of surfaces was carried out. In addition, the effect of the thickness of UHPFRC elements on the fibre content and orientation indicators was also assessed.

KEYWORDS: Ultra high performance fibre reinforced cementitious composites (UHPFRC), non-destructive test (NDT), Inductance, Fibre content, Fibre orientation.

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1

INTRODUCTION

1.1. FRAMEWORK

Ultra high performance fibre reinforced cementitious composite (UHPFRC) refers to a family of advanced cementitious materials with improved matrix packing density, very low water/binder ratio ($w/b < 0.2$) and high amounts of short high strength steel fibres (Abrishambaf, Pimentel and Nunes, 2017). Recently, UHPFRCs have become one of the most important cementitious materials used in building construction for strengthening the existing structures, due to their superior performances in terms of compressive strength, energy absorption capacity, ductility and durability in comparison to the normal reinforced concretes.

UHPFRC has the typical compressive strength in between 150-250 MPa. The tensile strength of an UHPFRC element is normally in the range between 7-15 MPa, and is highly dependent on the type, content, and orientation of the fibres with respect to the direction of the applied stresses (Abbas, Nehdi and Saleem, 2016). The tensile behaviour of an UHPFRC element can be enhanced significantly by adding the steel fibres, since the fibres are able to transfer stresses across the crack surfaces. Comparing to the conventional concrete, UHPFRC exhibits remarkable qualities in terms of durability due to the lower porosity, which exhibits a great resistance to the harmful agents and can resist in aggressive environmental conditions containing chlorides, sulphates or other aggressive substances.

It has to be mentioned that, the orientation of the fibres has a great impact on the tensile behaviour and a notable enhancement in the hardening stage of an UHPFRC element (Abrishambaf, Pimentel and Nunes, 2017). Therefore, in the past decade more research has focused on developing reliable quality control methods for UHPFRC, which can be used in-situ avoiding the need to extract core samples from the final structure.

The developments on non-destructive test (NDT) methods for assessing the properties of UHPFRC elements have started in 2010. The recent discoveries by different groups of researchers in different universities started by introducing a C-shaped magnetic probe with copper wire windings on its legs, which was able to measure inductance. The proposed NDT method was improved by time and was able to overcome the limitations of each proposed procedure, for instance; in terms of being able to get inductance measurements in different specimens with different dimensions and improvements in deriving the equations of fibre content and fibre orientation indicators.

The latest version of NDT method was proposed at FEUP, which was able to get inductance measurements on thin UHPFRC elements; moreover, the reliable equations of fibre content and fibre orientation indicators were derived in which only inductance measurements in two perpendicular directions of each point on the UHPFRC element were needed. The reliability and correctness of the results were assured by using image analysis techniques.

Furthermore, another group of researchers applied the developed magnetic probe at FEUP on their experimental campaign to consider the influence of local fibre distribution on the tensile behaviour of an UHPFRC slab element (Shen and Brühwiler, 2020). The outcome of their experimental campaign approved the correctness and reliability of the achieved results at FEUP by using the magnetic probe.

1.2. OBJECTIVES OF THE PRESENT WORK

The main objective of the present work is to assess the influence of the key factors for implementing the magnetic NDT method on UHPFRC elements. The inductance measurements taken with a magnetic probe are affected by several factors related to the UHPFRC element's size, quality of the tested surface and casting direction. Therefore, the contribution of third direction measurements, the effect of surface roughness, the effect of casting direction, and the impact of thicknesses in UHPFRC elements will be assessed in the present work.

1.3. ORGANIZATION OF THE PRESENT WORK

The present work starts with a literature review on UHPFRC main characteristics and on NDT methods proposed for the assessment of fibre dispersion and fibre orientation in UHPFRC elements in Chapter 2.

Chapter 3 focuses on the magnetic probe developed at FEUP. It discusses the way it works, the implementation of the theoretical model, and the process of deriving the equations of fibre content and fibre orientation indicators.

Chapter 4 concentrates on the influence of the third direction measurement of the inductance. In this chapter, the experimental campaign carried out on small cubic specimens is described. The goal of this chapter is to clarify if the third direction measurement can be neglected or not.

Chapter 5 gives more attention to the influence of the different types of surfaces on UHPFRC elements and the influence of the casting direction. In this chapter, the effects of casting direction (vertically or horizontally) and the surface roughness (cast, moulded, and smoothed) are discussed.

In Chapter 6, the thickness effect on the inductance measurements is evaluated. In this chapter, the influence of the thickness of the UHPFRC elements is discussed to define the maximum height up to which the fibres can affect the results. In this chapter, cylindrical specimens with large height are used as a starting point, afterward the measurements are repeated for smaller thicknesses by cutting the specimens in regular intervals.

Chapter 7 presents the main conclusions derived from the experimental campaign tests done in several specimens in order to enlighten the influence of each factor on fibre content and fibre orientation indicators. It discusses the limitations of the present work and suggests alternative studies for the future work.

2

ULTRA HIGH PERFORMANCE FIBRE REINFORCED COMPOSITES

2.1. DEFINITION OF UHPFRC

In the past decade, much research has focused on non-destructive measurements (NDT) done on steel fibre reinforced concretes (SFRCs), or Ultra-high performance fibre reinforced cementitious composites (UHPFRCs) to determine fibre content and fibre orientation in the hardened state. UHPFRCs have recently become one of the most successful and effective cementitious materials, which has started being used in civil structures before 1980s (Gu, Ye and Sun, 2015). Applying UHPFRCs to the structures can be continued either in the next generation of the infrastructures or being used in strengthening the existing structures.

UHPFRCs refer to a family of cementitious composites that contain a high amount of short and discrete steel fibres, which are equally embedded in an ultra-compact cementitious matrix with a large content of reactive powders and low water/binder ratio (Abrishambaf, Pimentel and Nunes, 2019). The key factor in developing the UHPFRC is to improve the micro properties of the mixture ingredients in order to enhance mechanical performance. Moreover, UHPFRCs demonstrate a very important improvement in strength, workability, durability, and ductility in comparison to the normal reinforced concretes (RCs) or high performance concretes (HPCs). It is worth to mention that the key factor to guarantee the ductile behaviour of the ultra-high performance concrete is to add the steel fibres. The exhibited mechanical and durability properties can lead to economical construction through reducing the cross sections of the structural materials. However, the high initial cost and limited codes of UHPFRC has limited its wider use in the construction industry. As a result, recently many researchers and investigators are trying to fill the knowledge gap in this innovative area and reducing the initial costs (Abrishambaf and Nunes, 2020) (Abbas, Nehdi and Saleem, 2016) (A. Matos, S. Nunes and C. Costa, 2016) (Azmeem and Shafiq, 2018) (Sidodikromo, Chen and Habib, 2019) .

As mentioned above, over the past few decades remarkable advances have been taken place in using SFRCs or UHPFRCs as an innovative material in building constructions and civil engineering structures such as tunnels, bridges, buildings, off-shore structures, hydraulic structures, and many other applications. Among all fascinating applications, some specific examples of UHPFRCs used in bridges are illustrated in Figure 1(a) for the Sakata Bridge in Japan and Figure 1(b) for the footbridge of Peace in South Korea.



(a)



(b)

Figure 1. UHPFRC bridges. Sakata-Mirai bridge, Sakata, Japan (a). Footbridge of Peace, Seoul, South Korea (b). (Gu, Ye and Sun, 2015), (Hendriks and Langeveld, 2017)

It is worth to mention that, in bridges, UHPFRCs can be applied in structural elements such as: beams, girders, deck panels, also as a protective layer to preserve structural elements when subjected to the harsh environmental conditions. Bridges built up of UHPFRCs in comparison to the bridges made up of traditional reinforced concretes, display a very slender appearance, much lower weight and better durability. Moreover, there are many buildings made up of UHPFRC but the most well-known ones are shown in Figure 2 and Figure 3 for the Louis Vuitton pour la Creation and the Museum of European and Mediterranean Civilizations in France, respectively (Gu, Ye and Sun, 2015), (Hendriks and Langeveld, 2017), (Azme and Shafiq, 2018).



Figure 2. Louis Vuitton pour la Creation in, Paris, France (Gu, Ye and Sun, 2015), (Azme and Shafiq, 2018).

The project of Louis Vuitton pour la Creation in Paris is well known due to its complexity in terms of geometry in which the cladding of the structure was built up of 19000 unique prefabricated panels of UHPFRC.



Figure 3. MUCEM, Marseille, France (Gu, Ye and Sun, 2015), (Hendriks and Langeveld, 2017), (Azmeem and Shafiq, 2018).

The Museum of European and Mediterranean Civilizations (MUCEM), which is shown in Figure 3, is located in the port area of Marseille in France. It was the first building in the world, which had the extensive use of UHPFRC, mostly the tree-like facades, columns, and brackets. Furthermore, UHPFRCs can be used in marine areas because of their great resistance to the aggressive environments. As an example, the Haneda Airport in Japan, which was extended over the sea, consists of a huge UHPFRC slab based on steel pipes (see Figure 4).



Figure 4. Haneda airport in Japan (Gu, Ye and Sun, 2015).

2.1.1. TYPICAL CONSTITUENT MATERIALS, MICROSTRUCTURE AND MIX-PROPORTIONS IN UHPFRC

This section focuses on the constituent materials, microstructure and mix proportions used in UHPFRCs. Generally, UHPFRCs consist of four essential components: powders and fine materials such as: ordinary Portland cement, quartz sand or fine sand, and silica fume, superplasticizers (also known as water reducers, mostly polycarboxylate ether-based), steel fibres, and water. This unique composite pursues the following characteristics of: low water/binder ratio, reduced porosity and therefore improved durability, and ductility due to the fibres used inside (Sidodikromo, Chen and Habib, 2019) (Abbas, Nehdi and Saleem, 2016) (Gu, Ye and Sun, 2015).

The key factor in producing UHPFRC is to enhance the homogeneity and packing density of the mixture. Since most of the failures in conventional concretes start by the damages at the interfacial transition zone (ITZ) between the cementitious matrix and aggregates, therefore this phenomenon is avoided in UHPFRCs by eliminating the coarse aggregates (Gu, Ye and Sun, 2015) (Abbas, Nehdi and Saleem, 2016). Figure 5 (a) illustrates the ITZ between the paste and sand particles in UHPFRC; moreover, Figure 5 (b) illustrates the bond between UHPFRC matrix and steel fibres.

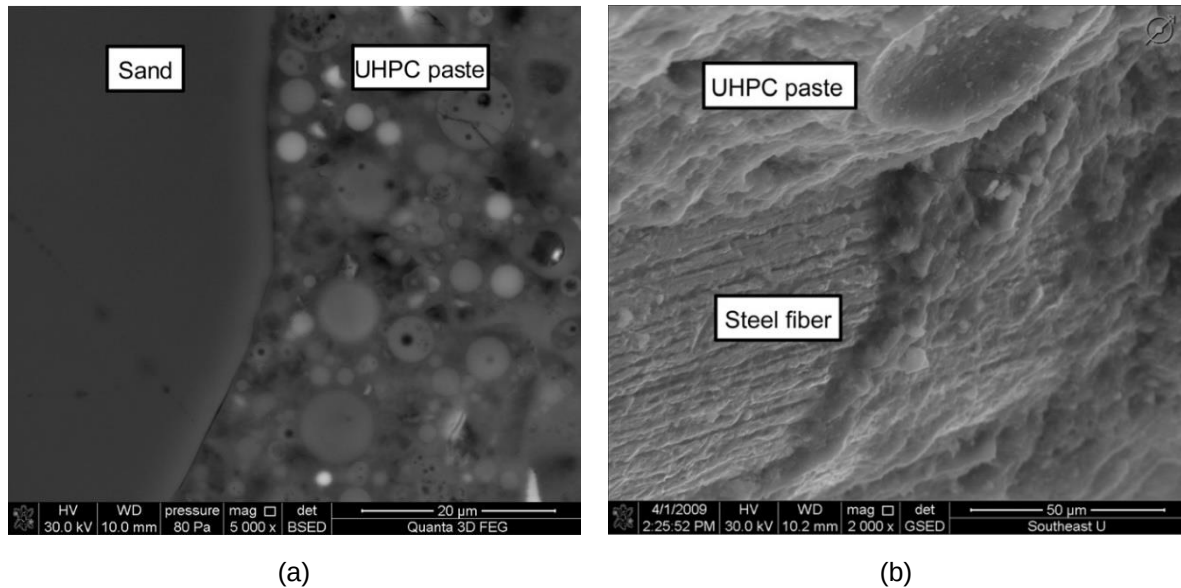


Figure 5. Interfacial transition zone (ITZ) between the cementitious matrix and aggregates (a), bond between the UHPFRC matrix and steel fibres (b) (Gu, Ye and Sun, 2015).

As shown in Figure 5, the steel fibre is fully wrapped by the matrix; moreover, the fibres can influence the cracking behaviour of UHPFRC, control the brittle fracture process, and improve the ductility of UHPFRC.

Fine sand used in UHPFRC has the general diameter between 150-600 µm and the ordinary Portland cement with the average diameter of 15 µm is the next largest particle used in UHPFRC. In comparison to the normal strength concrete (NS); a higher proportion of cement is used in development of UHPFRC. Furthermore, other smallest particles; limestone filler, silica fume, silica powder (glass powder), fly ash, and quartz powder being added to the mix, fills the voids between the various particle sizes, increases the mechanical and durability performances and improves the workability of the material (Sidodikromo, Chen and Habib, 2019) (Graybeal, 2006) (Dehghani and Aslani, 2020).

In UHPFRCs, a very low water/binder (w/b) ratio is applied typically between 0.13-0.20 (Abbas, Nehdi and Saleem, 2016). Due to the very low w/b ratio, only a part of the total cement hydrates and the non-hydrated cement can be replaced by crushed quartz, fly ash or blast furnace slag (pozzolanic materials) without reducing the compressive strength.

The reduced workability of the UHPFRC due to the lower w/b ratio can be overcome by adding an appropriate content of superplasticizer (SP), which is polycarboxylate ether (PCE). The SP dosage highly depends on the type of the used SP regarding to the compatibility between the mixture ingredients. For instance, an UHPFRC mixture containing limestone filler is more workable and compatible than an UHPFRC mixture that contains metakaolin, therefore a higher dosage of SP is suggested to be used in a mixture containing metakaolin. Figure 6 demonstrates UHPFRC mixes used in a test program by S. Nunes, M. Pimentel, A. Carvalho (2016), which proves the different dosage of SP used in two different mixes one with metakaolin (M2) and the other without metakaolin (M1). As it can be seen in Figure 6, the SP dosage in a mix containing metakaolin is higher than the mix without metakaolin. It has to be mentioned that the used SP dosage, ranges between 1-8 % by cement weight, but normally SP dosages of 1.4-2.4 % by cement weight are recommended (Abbas, Nehdi and Saleem, 2016) (Sidodikromo, Chen and Habib, 2019).

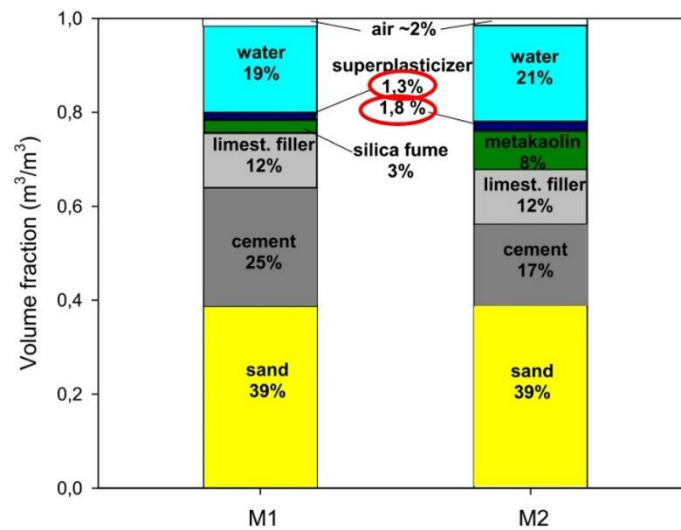


Figure 6. Comparing the SP dosage in two different UHPFRC mixes (Nunes, Pimentel and Carvalho, 2016).

There are different types of fibres with different lengths and cross section diameters. The most common used fibres in the development of UHPFRC are the straight steel fibres, hooked ended fibres and twisted fibres with a high tensile strength of 2000 MPa (Abbas, Nehdi and Saleem, 2016)(Abrishambaf, Pimentel and Nunes, 2017) (Pham, Tran and Sanjayan, 2020). Different types of steel fibres are illustrated in Figure 7.

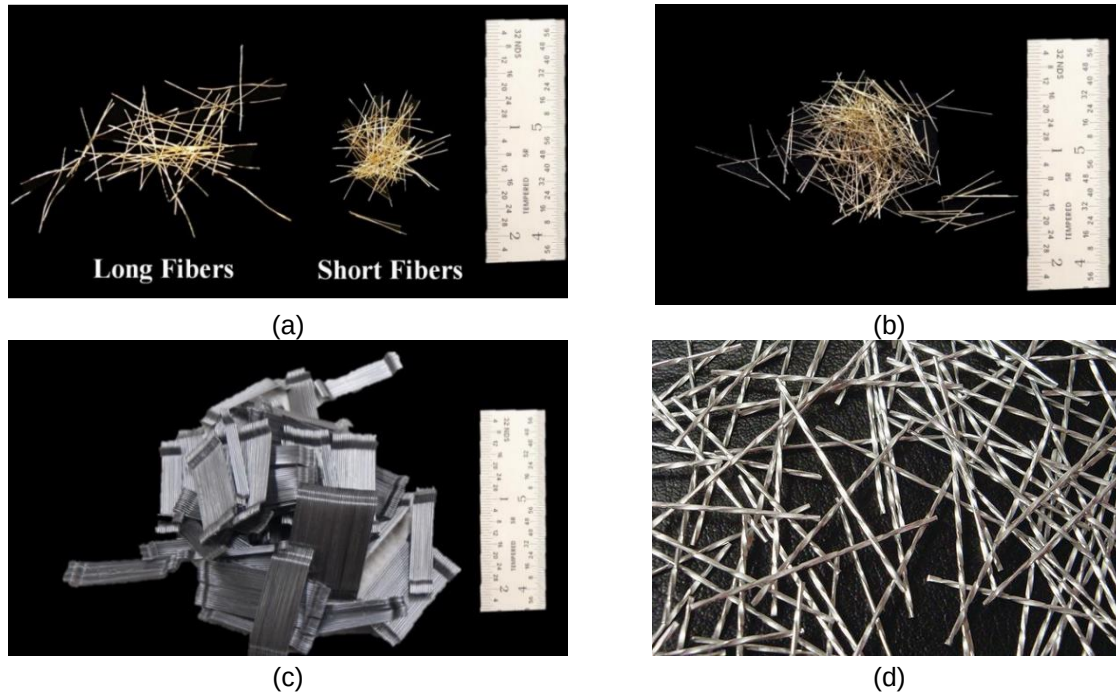


Figure 7. Different type of steel fibres. General length of straight steel fibres (a), straight steel fibres with 13 mm of length (b), hooked ended fibres (c), twisted steel fibres (d) (Haber *et al.*, 2018),(Buttignol, 2017) .

The constituents and general mix proportion for successful production of UHPFRCs are characterized in Table 1 and are compared with the mix proportion and ingredients of normal strength concrete (NSC), and high strength concrete (HSC).

Table 1. General constituents and mix proportions in NSC, HSC, and UHPFRC (Gu, Ye and Sun, 2015),(Abbas, Nehdi and Saleem, 2016).

	NSC	HSC	UHPFRC	UHPFRC constituent range (% by weight)
<i>Component (kg/m³)</i>				
Portland cement	<400	400	600-1000	27- 40
Coarse aggregate	≈1000	900	—	—
Sand	≈700	600	1000-1200	35-45
Silica fume	—	40	50-300	6-12
Reinforcement/Fibres	designed	designed	40-250	0-8
Superplasticizer	—	5	10-70	0.5-3
Water	>200	100-150	110-260	4-10
<i>Other parameters</i>				
Maximum aggregate size (mm)	19.0-25.5	9.5-12.5	0.15-0.6	
w/c ratio (by weight)	0.40-0.70	0.24-0.38	0.14-0.27	
w/b ratio (by weight)	—	<0.28	<0.20	

2.1.2. MECHANICAL AND DURABILITY PROPERTIES OF UHPFRC ELEMENTS

2.1.2.1. COMPRESSIVE BEHAVIOUR

One of the most important mechanical properties in designing any kind of concrete structure is the compressive strength. Normally, UHPFRC has the typical compressive strength in the range between 150-250 MPa. Moreover, UHPFRC designates a linear elastic behaviour up to the 70-80 % of its compressive strength. It has to be mentioned that adding fibres only slightly increases the compressive strength of the UHPFRC; however, the main influence of fibres is on the post peak stage in which a softening behaviour can be observed. The failure of an UHPFRC element without fibres is very brittle. (Gu, Ye and Sun, 2015) (Abbas, Nehdi and Saleem, 2016) (Yoo and Banthia, 2016). Figure 8 (a), (b) compares the stress-strain diagram of two UHPFRC elements one with 1.0-2.5% of fibres and the other one without fibres.

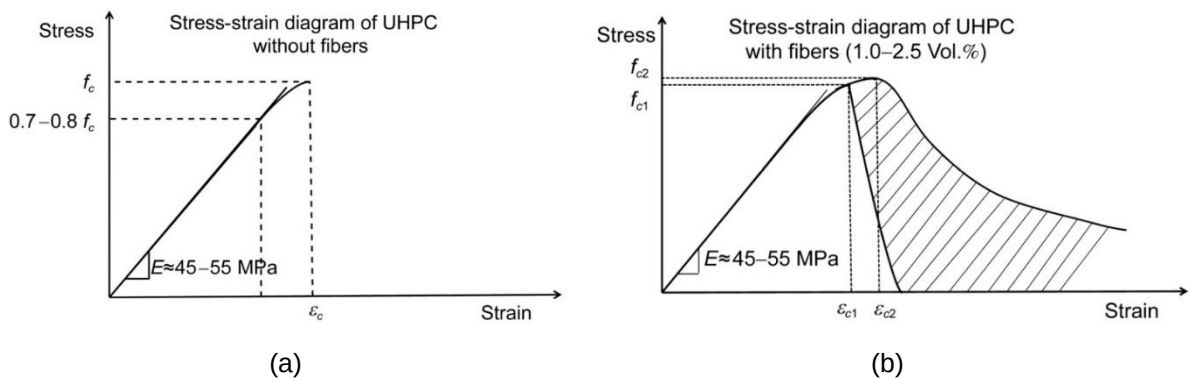


Figure 8. Comparison of stress-strain diagram in UHPC element (without fibres) (a), UHPFRC element with 1.0-2.5% fibre content (b). (Gu, Ye and Sun, 2015)

According to Figure 8, in an UHPC element (without fibres), a descending branch (Softening branch) cannot be observed; however, in an UHPFRC element with fibres, a descending branch can be seen due to the bridge-crack effect of the fibres.

2.1.2.2. TENSILE BEHAVIOUR

The tensile strength of an UHPFRC structure is normally in the range between 7-15 MPa, and is highly dependent on the type, content, and orientation of the fibres towards the direction of the applied stress. Furthermore, the representation of the tensile behaviour of an UHPFRC element (containing high fibre content or well-oriented fibres) is illustrated in detail in Figure 9.

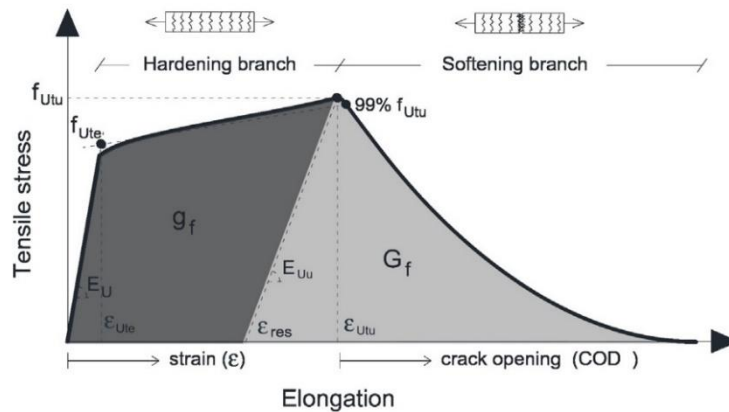


Figure 9. Tensile behaviour of a general UHPFRC element (Abrishambaf, Pimentel and Nunes, 2017).

In Figure 9, E_u is the elasticity modulus of the UHPFRC element, f_{Ute} and ε_{Ute} are the notional matrix cracking stress and strain, f_{Utu} and ε_{Utu} are the post cracking tensile stress and corresponding tensile strain. g_f is the energy dissipated per unit volume, E_{Uu} and ε_{res} are the elasticity modulus and the residual strain at unloading, and G_f is the energy dissipated in the post-peak stage per unit surface area of the macro-crack. The tensile response of UHPFRC is characterized by an initial elastic branch, which is followed by strain hardening up to the peak stress. After the peak stress, strain localization occurs with a large energy dissipation prior to complete stress release (Abrishambaf, Pimentel and Nunes, 2017).

2.1.2.3. FLEXURAL BEHAVIOUR

It is proved that steel fibres have a great impact on the flexural properties of UHPFRCs, which means that by increasing the fibre dosage, the flexural strength of an UHPFRC element increases linearly (Abbas, Nehdi and Saleem, 2016). Steel fibres play an important role in absorbing the tensile stresses and preventing the intergrowth of the micro cracks. In addition, the flexural strength of an UHPFRC element can be improved significantly using the hybrid mixture of steel fibres in comparison to the individual addition of steel fibres (Abbas, Nehdi and Saleem, 2016; Gu, Ye and Sun, 2015; Haber *et al.*, 2018; Yoo and Banthia, 2016).

2.1.2.4. DURABILITY PERFORMANCE

Additionally, UHPFRCs have remarkable qualities in terms of durability. The total porosity of UHPFRC is much lower than NC, as a result, UHPFRC shows a great resistance to harmful agents and can resist very well in the environments containing chloride and sulfate. Therefore, for engineers to build up a structure in a severe environmental condition, performing UHPFRCs would be the priority (Gu, Ye and Sun, 2015).

2.1.3. INFLUENCE OF CASTING AND FIBRE ORIENTATION ON THE TENSILE BEHAVIOUR OF UHPFRC

In a previous work done by Abrishambaf, Pimentel and Nunes (2017) an experimental campaign was carried out to investigate the influence of fibre orientation on the tensile behaviour of UHPFRC elements. In this campaign, specimens with two fibre dosages of 1.5 % and 3.0 % with different fibre orientations (not-oriented, oriented 0° , oriented 90°) were involved. The tensile behaviour of the specimens were determined by using uniaxial tensile tests (UTT). The results of tensile stresses of this experimental campaign are shown in Figure 10.

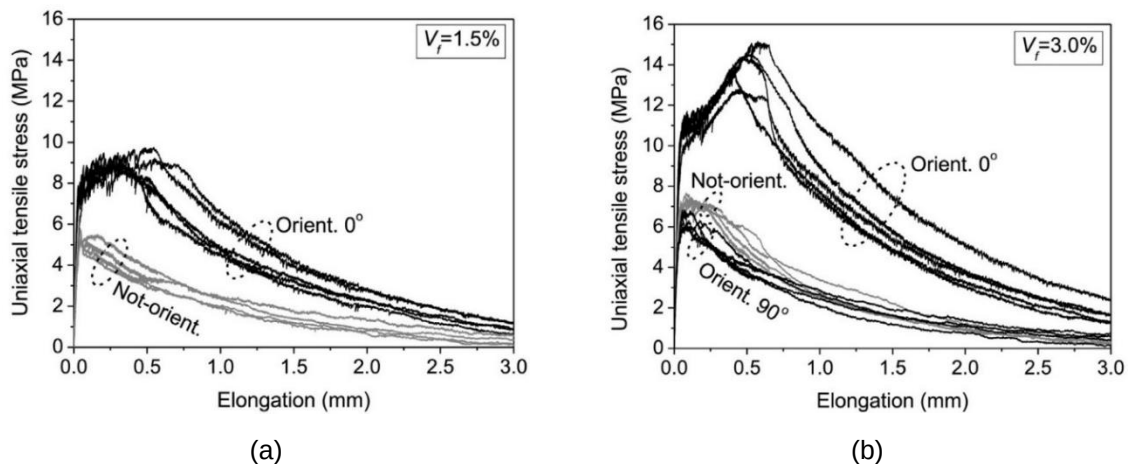


Figure 10. Uniaxial tensile tests in specimens with 1.5% volume fraction of fibres (a), and specimens with 3.0% volume fraction of fibres (b) (Abrishambaf, Pimentel and Nunes, 2017).

Moreover, an image analysis technique was employed to evaluate the fibre orientation distribution regarding to the direction of the applied stresses. This huge range of fibre orientation profiles was achieved by using a magnetic orientation set-up, which was able to orient the fibres during casting. This test set-up is explained in detail in Chapter 3 and Chapter 4.

As can be seen in Figure 10, in most of the curves the three main phases can be observed; elastic, hardening, and softening. The only exceptions are the non-oriented specimens with 1.5% of fibre dosage. Furthermore, both fibre content and fibre orientation have impacts on the tensile strength of the specimens. The fibre orientation has shown a very remarkable impact on the tensile response of UHPFRC; a notable development in the hardening stage. The results show that the orientation of the fibres had more impact than doubling the fibre content from 1.5% to 3.0% (Abrishambaf, Pimentel and Nunes, 2017). To better understand the UTT test results, the crack patterns of the mentioned specimens are shown in Figure 11.

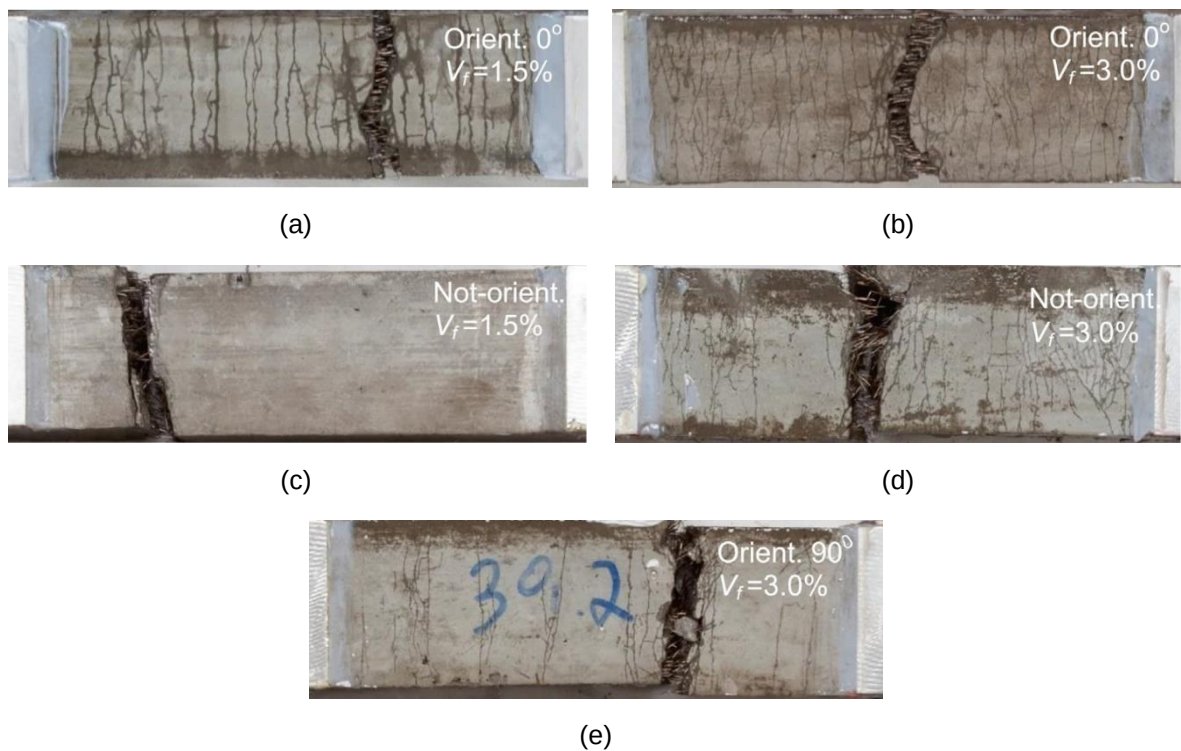


Figure 11. Representative crack patterns for uniaxial tensile tests, specimens with 1.5% fibre content (a), (c), specimens with 3% of fibre content (b), (d), (e). (Abrishambaf, Pimentel and Nunes, 2017)

According to Figure 11, in specimens with oriented fibres along 0°, the number of the cracks increased by increasing the fibre content. As can be seen in non-oriented specimens with the fibre content of 1.5% (c), only a single crack was formed in the specimen. Moreover, the specimens with the fibre content of 3% not-oriented or oriented along 90° (d), (e) exhibited a more complex crack patterns with more irregular crack spacing.

2.2. LITERATURE REVIEW OF DIFFERENT NDT METHODS FOR THE ANALYSIS OF FIBRE DISPERSION AND ORIENTATION IN UHPFRC

2.2.1. SEVERAL POSSIBLE APPROACHES FOR THE ANALYSIS OF THE FIBRE DISPERSION IN UHPFRC

As discussed in previous sections recently the use of SFRCs and UHPFRCs in structural applications has increased significantly. This increase has to be accompanied by reliable controlling methods for determining the fibre content and fibre orientation so that the safety of the structures could be guaranteed. As discussed in the previous section 2.1.3 the dispersion of the fibres plays a critical role on the tensile behaviour of UHPFRC elements. Moreover, the proposed method should be economical and feasible for being used in the construction site.

The methods are divided into two groups of destructive and non-destructive methods. The most common destructive method is crushing the specimens and counting the fibres manually. This method can only give the information about the fibre dosage; however, it does not give any information related to the fibre orientation. As drawbacks of this process one can refer to its being time-consuming and environmentally unfriendly procedure. Alternative destructive methods can refer to image analysis and computerised tomography (CT-scans). These procedures, give detailed information about the fibre content and orientation; however, they are destructive.

Nevertheless, non-destructive methods (NDT) refer to the techniques, which give a very detailed information related to the fibre content and fibre orientation in UHPFRC elements without crushing or cutting and taking core samples from the specimens. These methods are based on the ferromagnetic properties of the steel fibres used inside the SFRCs or UHPFRCs. As an example of these techniques, one can refer to sensors (inductive coils) or magnetic probes. The NDT or magnetic method is easy, economic, and repeatable. These techniques guarantee the high reliability and repeatability of the results. Moreover, due to the limitations of the non-destructive measurements regarding to their high costs, and not being able to be used in worksites, these methods are less attractive.

Recently, more advances occurred regarding to the non-destructive methods. Next sections explain more about magnetic methods and their improvement within the past decades in different universities (Cavalaro *et al.*, 2015; Lampropoulos, Tsioulou and Paschalis, 2012; Nunes, Pimentel and Carvalho, 2016; Segura-Castillo *et al.*, 2018; Torrents *et al.*, 2012).

2.2.2. NDT METHOD PROPOSED BY THE TEAM FROM POLITECNICO DI MILAN (Faifer, Ottoboni and Toscani, 2010)

This section focuses on the work developed by a research team involving the experts of both Electrical and Structural Engineering faculties of the Politecnico di Milano University. Their activity in this research area started in 2010 and was focused on the influence of the steel fibres on the effective magnetic permeability of the composites. Their aim was to reach to a technique that not only gives the information about the fibre concentration and fibre orientation in SFRCs, but also it could reach to reliable information about the size of the steel fibres used inside the composites.

Their research led to a new probe with two couples of windings. A couple of windings provided *mmf* (magneto motive force) to support the flux; however, the other couple was used to collect the *emf* (electro motive force). Magneto motive force refers to the quantity achieved by multiplying the magnetic flux (Φ) and reluctance (R) in a magnetic circuit ($F_m = \Phi \cdot R$) and is analogous to the electromotive force ($V = I \cdot R$). Therefore, an equivalent Ohm's law is presented for magnetic circuits, and is explained in detail in chapter 3. According to their conclusions, the parameter ΔL_v , which was

sensitive to the fibre orientation and fibre concentration, could be acquired by the difference of the mutual inductance measured by placing the probe on the surface of the SFRC and that gained by placing the probe in air away from any magnetic objects. Mutual inductance refers to the property of a coil, which influences the current and voltage in a secondary coil; however, inductance refers to a magnetic flux produced for a given electric current ($L = \frac{\Phi}{I}$). According to this team, in order to enhance the sensitivity of the mutual inductance it was suggested to place the windings as close as possible to the surface of the SFRC element, as a result the windings were placed on the probe at the end of its legs (Faifer, Ottoboni and Toscani, 2010).

Consequently, the manufactured magnetic probe for this subject consisted of a C-shaped N-87 ferrite core, with the cross section area of $20 \times 30 \text{ mm}^2$, core length of 125mm and the height of 90mm. The probe consisted of 40 turns of coil on both its legs. Figure 12 (a) represents the magnetic probe and Figure 12 (b) shows the FEM simulation of the magnetic flux density of the probe (Faifer, Ottoboni and Toscani, 2010).

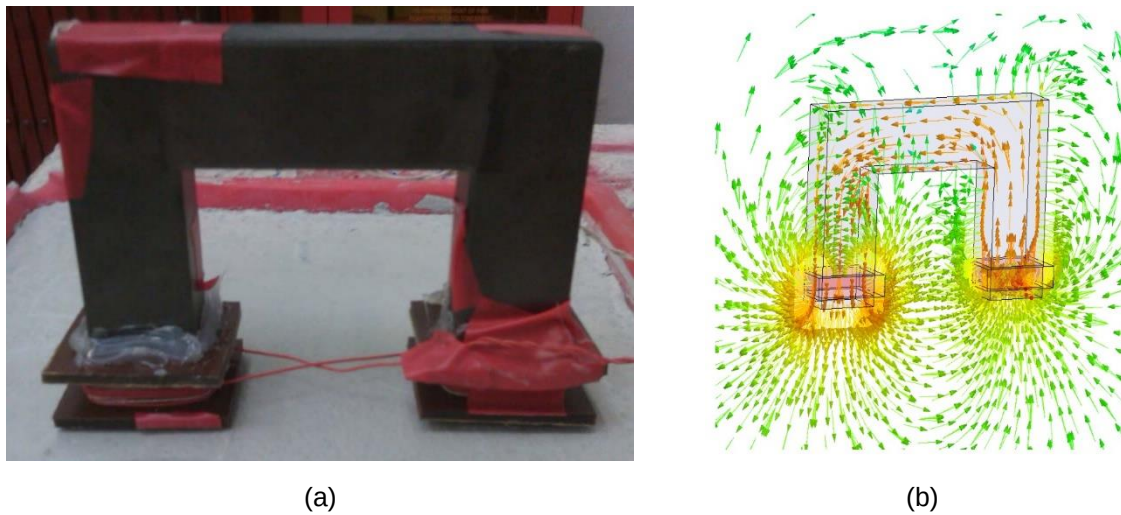


Figure 12. Magnetic probe used proposed by the researchers of the Polytechnic University of Milan (a), FEM simulation of the magnetic flux density (b). (Faifer, Ottoboni and Toscani, 2010)

M. Faifer, R. Ottoboni, S. Toscani carried out an experimental campaign in order to evaluate the fibre concentration and fibre orientation in three different specimens with three distinct fibre dosages. One specimen with the fibre dosage of 50 kg/m^3 (called S50), the other one with the fibre dosage of 100 kg/m^3 (called S100) and both not-oriented specimens. The third one had a homogeneous orientation of the fibres (by placing fibres manually on the cardboards and locating in three layers inside the fresh concrete) with the fibre dosage of 84 kg/m^3 (called Sample). In the third specimen, larger fibres were used and all the specimens had the dimensions of 100 cm long, 50 cm width and 3 cm thick. The mutual inductance results achieved from their measurements as a function of frequency is shown in Figure 13(a). Furthermore, they evaluated the results of the difference between the mutual inductances in two perpendicular directions (ΔL), and is presented in Figure 13(b).

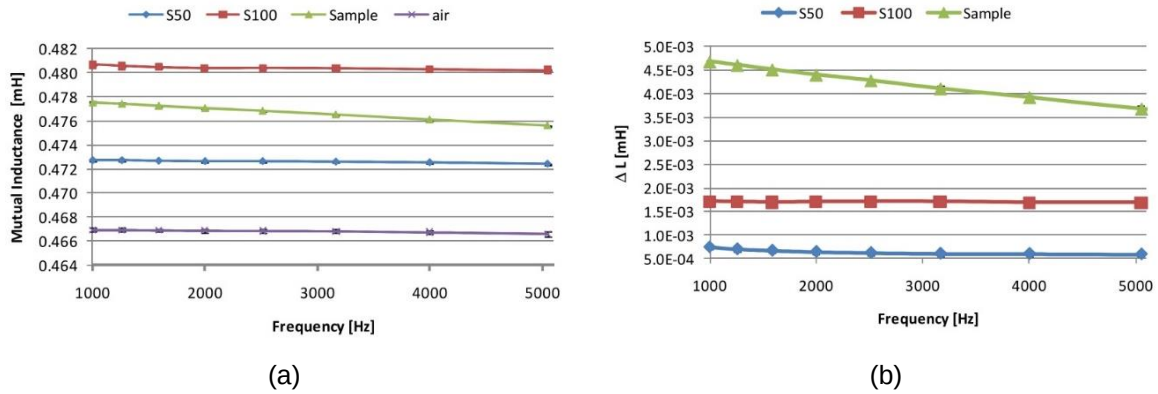


Figure 13. Experiment results of the tests done in the Politecnico di Milano University. Mutual inductance results (a), ΔL (difference between the mutual inductances) (b) (Faifer, Ottoboni and Toscani, 2010).

As can be seen in Figure 13(a), the mutual inductance results are higher in S100 than in the Sample and S50. It is a proof for detecting the concentration factor of the fibres; from the highest to the lowest, which means the higher the concentration of the fibres the higher the mutual inductance results. Moreover, it has to be mentioned that the mutual inductance results measured for the Sample is placed between those measured for S50 and S100, which proves the accuracy and correctness of the results. According to Figure 13 (b), it can be proved that the difference in the mutual inductance measurements by placing the probe along and perpendicular to the average fibre orientation shows higher values in Sample (oriented specimen) than the other two specimens. It can be concluded that, the orientation of the fibres can be obtained simply by rotating the probe and finding the maximum value of the mutual inductance.

Later on in 2011, this research team changed the position of the windings on the magnetic probe used for the measurements. The magnetic probe almost with the same dimensions; however, using a different magnetic circuit of the probe, and this time by placing the windings on the top part of the coil with 78 turns (increasing 38 turns). See Figure 14 (a) for the magnetic probe and Figure 14 (b) for the simulation of the flux density (Faifer *et al.*, 2011).

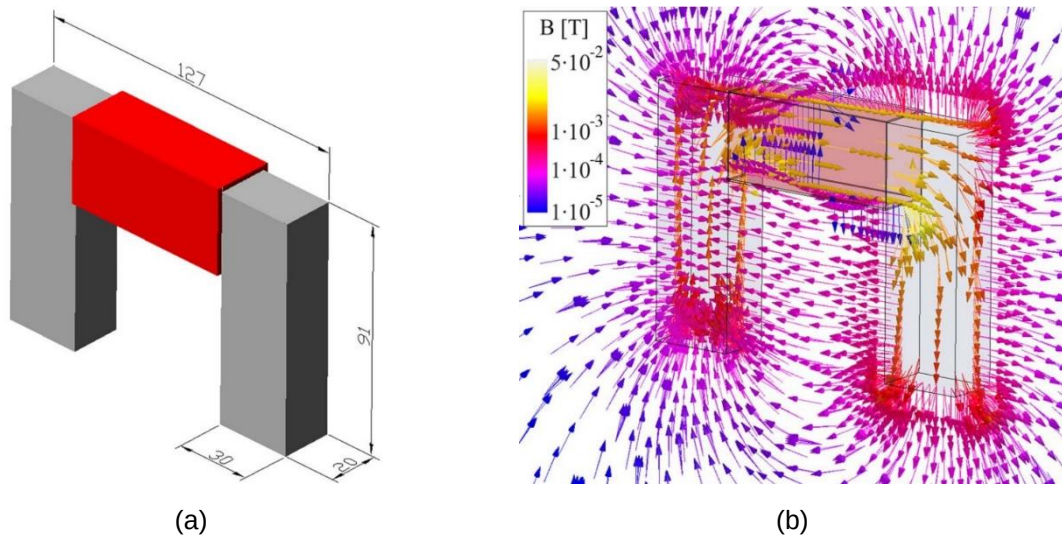


Figure 14. Sketch of the improved probe in 2011 by M. Faifer, R. Ottoboni, S. Toscani (a), simulation of the flux density of the probe (b) (Faifer *et al.*, 2011).

According to Figure 14 (b), it is observed that in the area close to the windings the intensity of the magnetic field is higher in comparison to the other sections of the probe.

In this experimental campaign, the inductance measurements were done on three different specimens of $100\text{cm} \times 50\text{cm} \times 2.5\text{cm}$ one without any steel fibres (S00), second one with a fibre concentration of 50 kg/m^3 (S50), and the last one with the fibre concentration of 100 kg/m^3 (S100). The measurements were taken on the centre point of the specimens in two directions of along the fibre orientation direction and perpendicular to the fibre orientation direction (Faifer *et al.*, 2011). The main conclusion of the results is represented in Figure 15.

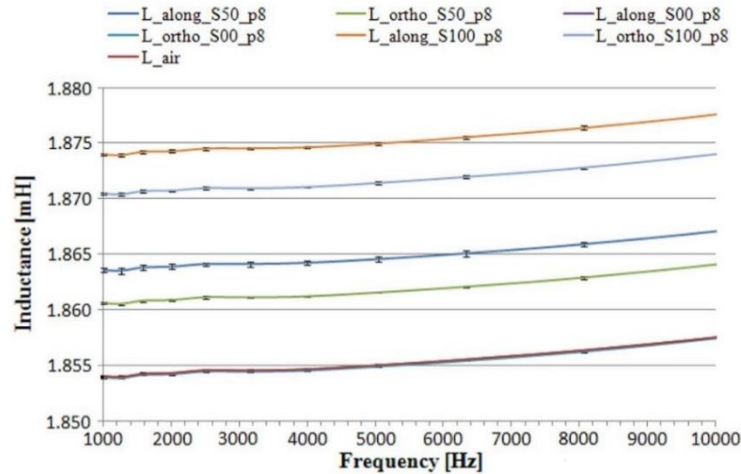


Figure 15. Inductance results of the measurements done on three types of specimens in the centre point in two perpendicular directions (Faifer *et al.*, 2011).

According to the results shown in Figure 15, the inductance results of the specimen S00 and air are the same, which means that the plain concrete without any fibres has the same magnetic permeability as air. Moreover, the specimens with higher concentration of fibres have higher inductance results ($LS100 > LS50 > LS00$).

Furthermore, the inductance results along the orientation of the fibres are higher than the results perpendicular to the direction of the orientation of the fibres. An important point is the higher values for the inductance results with the improved probe in comparison to the results gained with the previous probe. It can be justified in the way that the improved probe had higher number of wire turns (78 turns) rather than the previous probe with 40 number of turns (Faifer *et al.*, 2011) (Ferrara, Faifer and Toscani, 2012) (Ferrara *et al.*, 2012) (Faifer *et al.*, 2013).

In conclusion, this team revealed a huge improvement in NDT measurements; however, it was not able to give clear information related to the specimens with unknown amounts of fibres.

2.2.3. NDT METHOD PROPOSED BY THE TEAM FROM UNIVERSITAT POLITÈCNICA DE CATALUNYA (Cavalero *et al.*, 2015)

A group of experts in the University of Barcelona, Spain began their research on non-destructive methods in 2012. They started their processes by measuring the content and orientation of the fibres in cubic specimens of $150 \times 150 \times 150\text{ mm}^3$ by using a sensor (inductive coil) (Torrents *et al.*, 2012). In fact, the specimens were placed in a plastic element with the dimensions of $150 \times 170 \times 170\text{ mm}^3$, which had

discontinuous coils connected by a single wire around it. This equipment consisted of a LCR impedance analyser, which generated an electric current flow inside the coil (Cavalaro *et al.*, 2015). The current flow was able to produce a magnetic field inside the coil and the ferromagnetic properties of the fibres inside the specimens were able to increase the magnetic permeability. Consequently, the inductance was measured (see Figure 16).

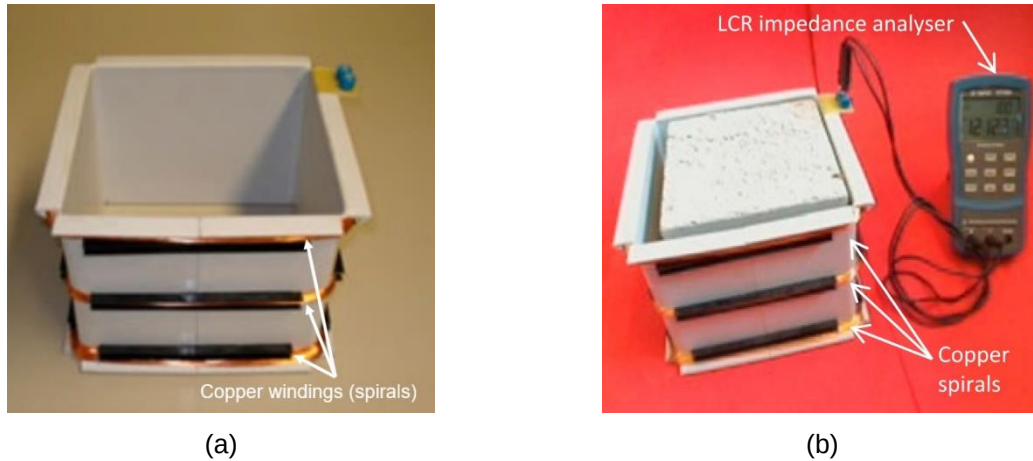


Figure 16. Process of measurements done on cubic specimens. Formwork used for the test (plastic element) (a), measuring the inductance of the specimen placed inside the formwork (b) (Torrents *et al.*, 2012).

As can be observed in Figure 16, there are three layers of copper windings with 7.5 cm spacing in between each other. The copper cable had the cross section diameter of 0.2 mm with the total number of 2,354 turns and 1,600 mm length.

The main purpose of using discontinuous coil for this set-up of measurements was to get as homogenous magnetic field as possible and avoiding the magnetic field changes in the edges and centre points. However, the drawback of this process was to wrap the coils manually, which were 2,354 turns in total (Torrents *et al.*, 2012). It has to be emphasized that the process to measure the inductance was by placing the specimen inside the formwork (plastic element) and define an axis and measure the inductance, then rotate the specimen to the other pre-defined axis and measure the inductance.

Finally after doing all the measurements in all three main perpendicular axis (X, Y, Z), the mean value of all the measurements were calculated, which represented the fibre content of the specimens. An experimental campaign consisting of cubic specimens with different fibre dosages were carried out. The fibre dosages were known and with the increase of 15 kg/m^3 . Moreover, the fibres used were the hooked ended fibres with the length of 50 mm and cross section diameter of 1 mm. The results obtained from this campaign revealed a linear relation between the fibre dosage and inductance measurements (Torrents *et al.*, 2012) (see Figure 17).

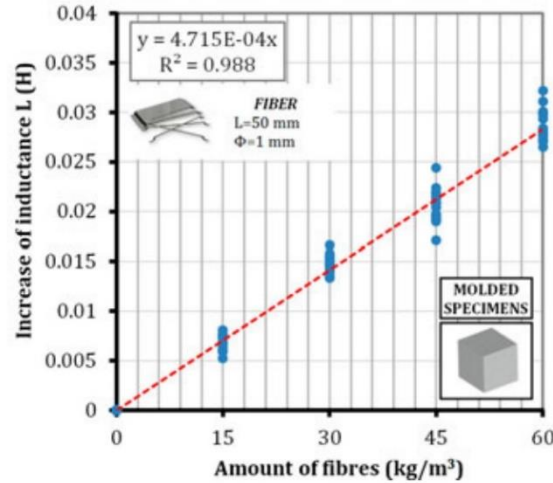


Figure 17. Application of an inductive method for several cubic specimens (Torrents *et al.*, 2012).

The limitation of this test set-up was its suitability only for cubic specimens, which are almost impossible to extract from a real structure. Moreover, in this set-up it was only possible to get the results in three main perpendicular axis. Later on, this team tried to enhance and improve the procedure so that it can be used for any specimens with any shapes and dimensions with the possibility of inductance measurements in all directions. As a result, the cylindrical specimens were chosen to be studied more (Juan-García *et al.*, 2016). It has to be taken into account that the accuracy of the results highly depends on the homogeneity of the magnetic field. Therefore, a circular shaped coil was used instead of the square one, leading to a more homogenous magnetic field (Cavalaro *et al.*, 2016) (see Figure 18).

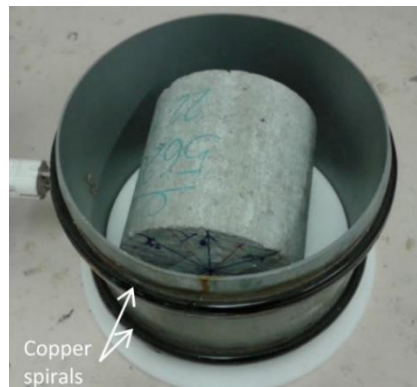


Figure 18. Improved method for inductance measurements of cylindrical specimens (Cavalaro *et al.*, 2016).

Unlike the previous test set-up the circular one consisted of two layers of copper winding with 13 cm of space in between, the interior diameter of 25 cm; moreover, the copper winding had the cross section diameter of 0.3 mm and the total number of 1,200 turns.

The experimental campaign included both cubic and cylindrical specimens. The cubic specimens had the dimensions of $150 \times 150 \times 150 \text{ mm}^3$, and the cylindrical specimens had a diameter of 150mm and height of 150mm with different fibre contents (Cavalaro *et al.*, 2016). All the inductance measurements were carried out in the improved test set-up shown in Figure 18. The results of the tests in cubic and cylindrical specimens are represented in Figure 19.

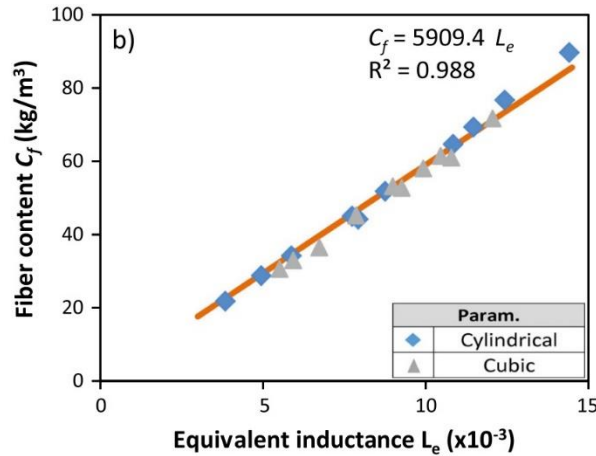


Figure 19. Results of inductance measurements done on cubic and cylindrical specimens (Cavalaro *et al.*, 2016).

As can be seen in Figure 19, there is a linear relation between the measured inductance and fibre content in all the specimens using the improved inductive coil. The results are the proof for the efficiency of the enhanced inductive coil, which can be used in specimens with different shapes and with the possibility of inductance measurements in any direction (Cavalaro *et al.*, 2016).

In conclusion, it has to be mentioned that this method is more suitable for the specimens cast in laboratory or by taking the cores from real structures. However, it still had limitations for not being able to be used in slabs or very thin elements, which are common in UHPFRCs. Moreover, in this experimental campaign, it was focused on SFRC elements with long steel fibres and still there is a knowledge gap for short steel fibres particularly with high fibre content, which are usual in the development of UHPFRCs.

2.2.4. NDT METHOD DEVELOPED AT FEUP (Nunes, Pimentel and Carvalho, 2016)

This section represents the achievements of a team consisting of researchers and expert professors of both Civil Engineering and Electrical Engineering faculties of University of Porto, Portugal that could overcome to the limitations of NDT methods proposed by previous researchers.

The NDT method proposed by S. Nunes, M. Pimentel, A. Carvalho (2016) was able to go further than the inductance measurements on cubic or cylindrical specimens and could be used on slabs or thin UHPFRC elements. Moreover, the team was able to derive the equations of the fibre content and fibre orientation indicators in relation with inductance measurements by using the analogy between the magnetic and electrical circuits. The team proved that the reliable fibre content and orientation factors only require two inductance measurements on each zone.

Furthermore, an orientation set-up for aligning the fibres in a preferential direction was proposed by the team, which was able to eliminate the manual orienting the fibres used by the previous researchers and making it feasible to orient large amounts of fibres with very short lengths.

It has to be taken into consideration that, the achieved conclusions were approved by using image analysis and mechanical testing. The magnetic probe proposed by this team is described in detail in Chapter 3.

An experiment campaign was carried out consisting of not-oriented (Random) and oriented specimens (oriented using the orientation set-up) with different fibre dosages in between 0.5%- 4%. The specimens consisted of fibres with three different lengths (6, 9, and 12 mm) and the cross section diameters of

0.175 mm. The tests were done on the plate specimens with the dimensions of $150 \times 304 \times 25 \text{ mm}^3$ so that later on DEWS (double edge wedge splitting) tests could be carried out. Application of DEWS tests was to characterize the tensile behaviour of the specimens (Nunes, Pimentel and Carvalho, 2016). The process of preparing the specimens in this campaign is shown in Figure 20. Additionally, the inductance measurements on specimens on a specific zone along the orientation of the fibres (X direction) and perpendicular to the orientation of the fibres (Y direction) are illustrated in Figure 21.

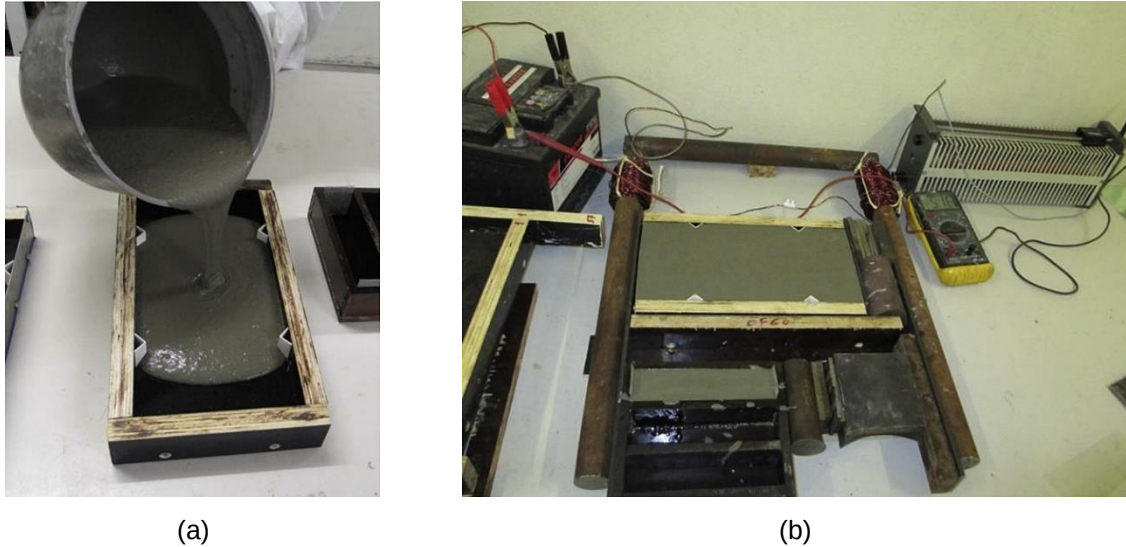


Figure 20. Process of preparing the specimens. Random specimens (a), oriented specimens inside the orientation set-up (Nunes, Pimentel and Carvalho, 2016).

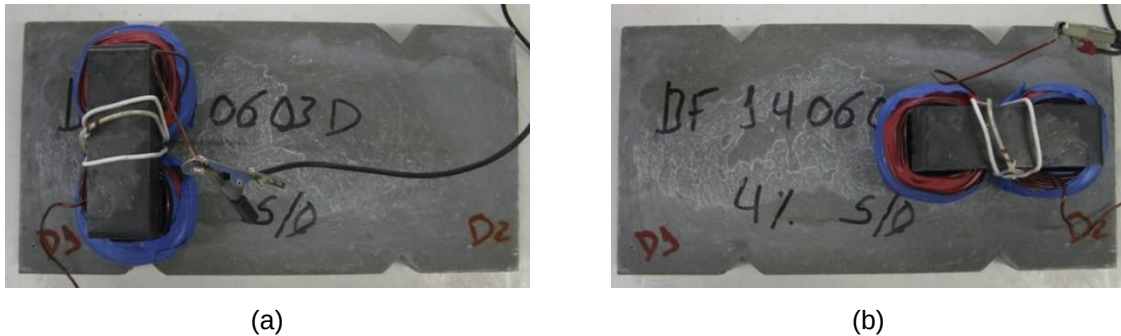


Figure 21. Measuring the inductance on UHPFRC elements. Inductance along Y direction (a), Inductance along X direction (b) (Nunes, Pimentel and Carvalho, 2016).

As can be seen in Figure 21, the inductance in different axis was measured by rotating the probe 90° or perpendicular to the measured axis. Furthermore, to better clarify the inductance changes in two directions, the results related to the oriented specimens with the fibre dosages of 1%, 2%, 3%, and 4% are designated in Figure 22.

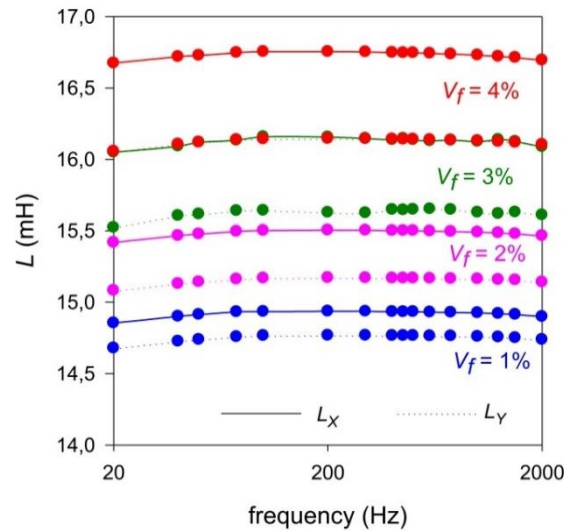


Figure 22. Inductance results in oriented specimens in the frequency range between 20-2000 Hz (Nunes, Pimentel and Carvalho, 2016).

According to the results shown in Figure 22, the inductance results in oriented specimens along the orientation of the fibres (L_x) is higher than the inductance results perpendicular to the orientation of the fibres (L_y), which approves the accuracy of the orientation set-up for aligning the fibres along a preferential direction (X axis). In addition, by increasing the fibre dosage, the inductance results are increasing as well, which assures the accuracy of the previous conclusions that inductance results can reveal information related to the fibre concentration and fibre orientation.

All the information related to the fibre content and fibre orientation indicators and the proposed equations are explained in detail in Chapter 3.

2.2.5. RECENT APPLICATION OF NDT METHOD DEVELOPED AT FEUP

A team consisting of the researchers from the L'Ecole Polytechnique Fédérale de Lausanne (EPFL), in Switzerland, carried out an experimental campaign using a magnetic probe developed at FEUP. Shen and Brühwiler, settled a test campaign focusing on the influence of the local fibre distribution on the tensile behaviour of UHPFRC.

X. Shen, E. Brühwiler prepared a slab element using an industrial premix with a fibre content of 3.8%, fibre length of 13 mm and cross section diameter of 0.175 mm. The dimensions of the slab element (named T1), were 1100×1100×50 mm³; furthermore, the specimen was cast by pouring the material in the centre point of the mould and letting it flow only by the action of the gravity (Shen and Brühwiler, 2020).

Afterwards, the NDT measurements were carried on both surfaces of the slab on specific points. In order to understand the tensile behaviour of the element, dog bone specimens had to be cut from the large slab, as a result a schematic figure of the dog bone specimens were marked on the slab and the locations of the measuring points were determined on each element (see Figure 23).

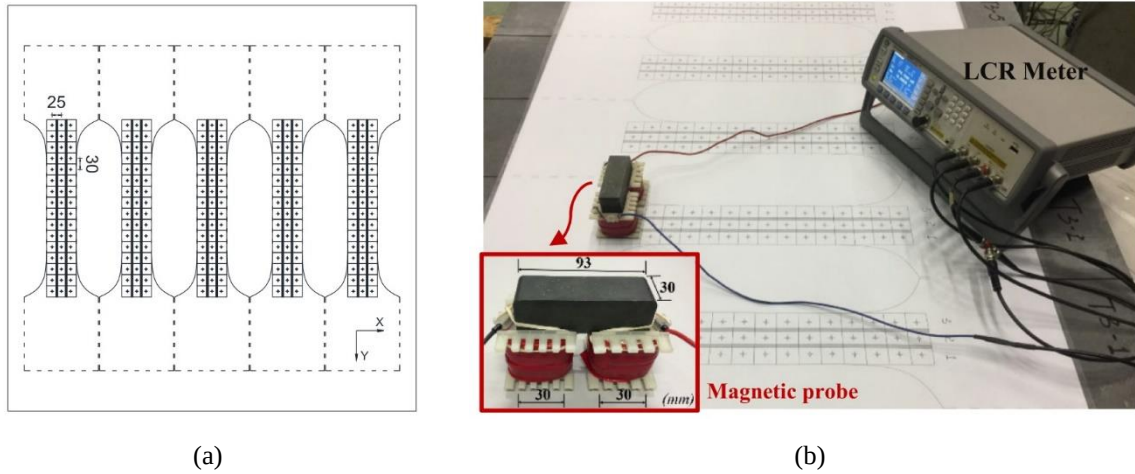


Figure 23. Inductance measurements using the magnetic probe. Location and direction of the measurements (a), test set-up (b) (Shen and Brühwiler, 2020).

The measurements were taken in two perpendicular directions (X and Y); moreover, the spaces between the measuring points were 2.5 cm from the X direction, and 3 cm from Y direction. The contour map results obtained for the fibre volume fraction in both surfaces is represented in Figure 24.

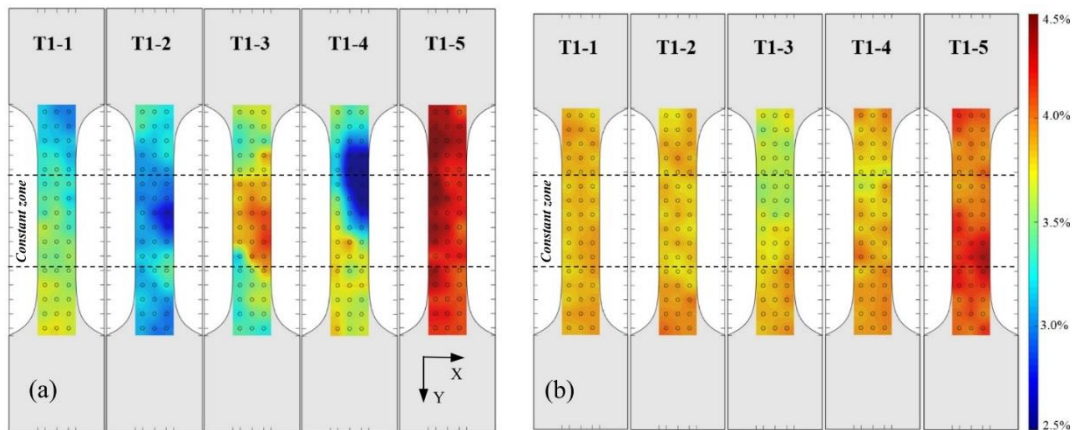


Figure 24. Contour map for fibre volume fraction (V_f). Casting surface (a), Moulded surface (b) (Shen and Brühwiler, 2020).

According to the results shown in Figure 24, it can be concluded that the distribution of the fibres is slightly higher and more uniform in the moulded surface rather than the casting surface. It can be due to the wall effect in the moulded surface, also another hypothesis according to the authors is that fibres in the casting surface were oriented vertically due to the flow direction of the material (Shen and Brühwiler, 2020). In addition, the results of the fibre orientation factor is illustrated in Figure 25.

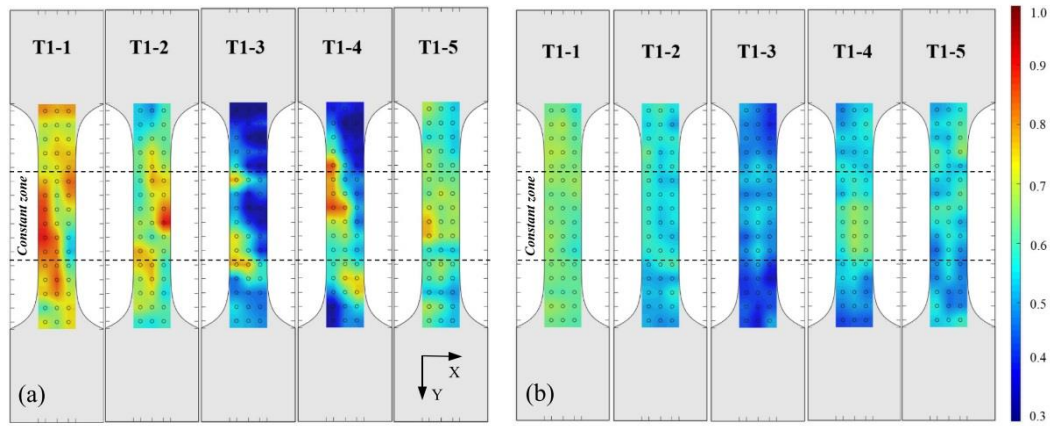


Figure 25. Contour map for fibre orientation factor. Casting surface (a), Moulded surface (b) (Shen and Brühwiler, 2020).

As can be seen in Figure 25, fibre orientation factor in both surfaces for the specimens near the casting point (T1-2, T1-3, T1-4) has larger scatter in comparison to the specimens far from the casting point (T1-1, T1-5). It can be concluded that the fibres were rotated by the flow of the material, and this rotation was perpendicular to the flow direction (Shen and Brühwiler, 2020).

Afterwards, direct tensile tests were carried out on the specimens and the results of the stress-strain diagrams of all the specimens are shown in Figure 26.

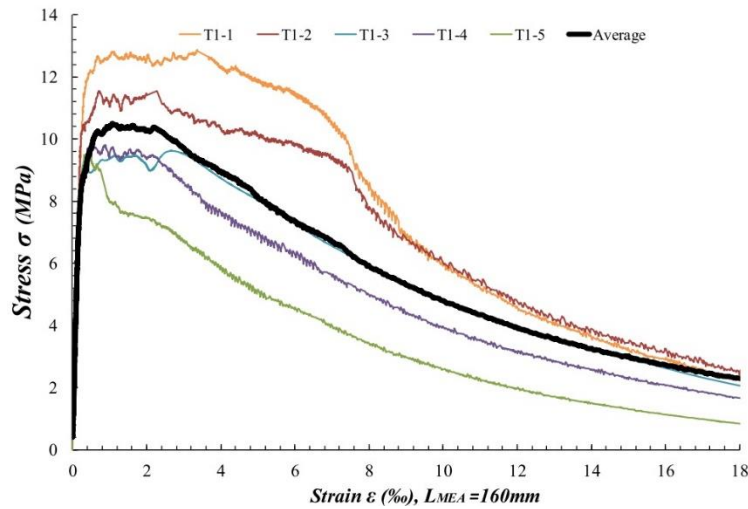


Figure 26. Stress-strain response of 5 specimens (Shen and Brühwiler, 2020).

According to the tensile test results shown in Figure 26, it can be concluded that even though all the specimens were cut from a single element but they represented different tensile behaviours. These different tensile behaviours are mainly related to the distribution and orientation of the fibres.

2.3. CONCLUSION

Overall, it can be concluded that the magnetic method improved in different universities had limitations. However, these limitations were improved by the time, and the latest version being proposed by FEUP was almost the most convenient one, which was able to overcome the previous limitations.

3

NDT METHOD DEVELOPED AT FEUP

3.1. NDT METHOD

As described in detail in Chapter 2, huge improvements have been revealed in the innovative field of NDT or non-destructive tests done on UHPFRCs since 2010. According to the latest improvements discussed in the previous chapter, a magnetic probe was proposed by S. Nunes, M. Pimentel, A. Carvalho in the University of Porto, Portugal (FEUP). This chapter focuses on the magnetic probes developed at FEUP. Moreover, it gives more detailed information related to the proposed theoretical model besides the equations of fibre content and fibre orientation indicators derived by this group of experts.

3.1.1. MAGNETIC PROBES DEVELOPED AT FEUP

An initial magnetic probe was designed to measure inductance, and to get the reliable indicators of fibre content and fibre orientation (Nunes, Pimentel and Carvalho, 2016). However, recently a novel version of the magnetic probe was developed at FEUP, which was able to accomplish significant goals. For instance, making the process of fabricating the probe easier, increasing the durability of the probe, and the most important to increase the precision of the achieved results.

Both magnetic probes consist of a U-shaped ferrite core (Siemens ferrite N47) consisting of a single copper wire coil around both legs of the core, see Figure 27.

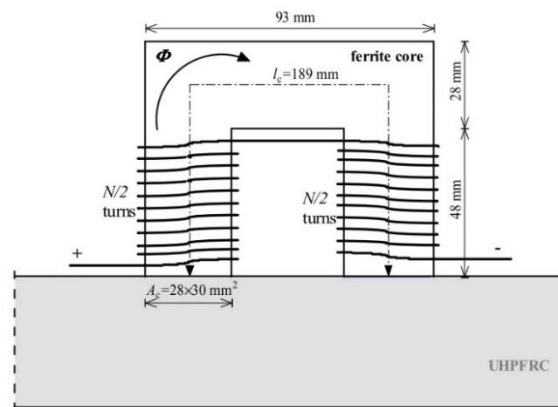


Figure 27. Schematic representation of the magnetic probe placed over a UHPFRC layer (Nunes, Pimentel and Carvalho, 2016).

The main difference between these two probes is the diameter of the copper wire used and consequently the number of the turns around the legs (See). By reducing the diameter of the wire in new probe, the number of the turns increased. It is proved that by increasing the number of the turns, the precision of the results increased significantly (Nunes and Pimentel, 2016). Figure 28 illustrates the two magnetic probes developed at FEUP.

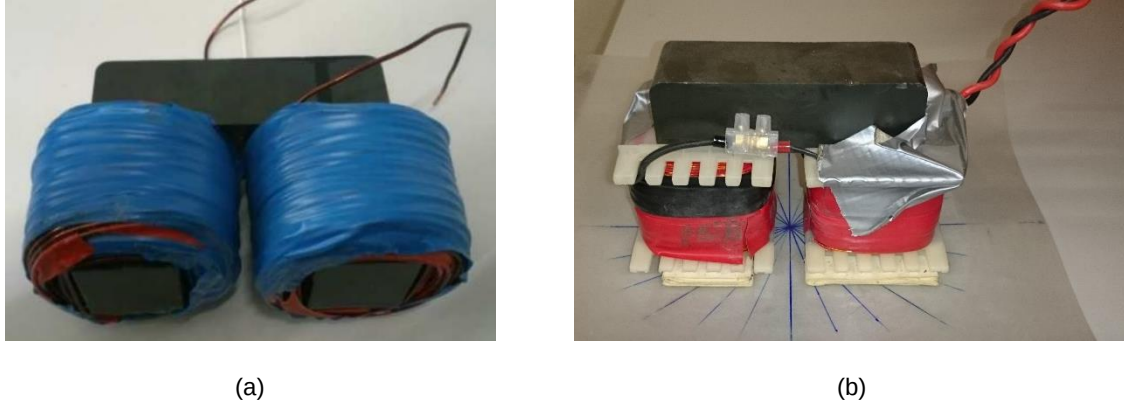


Figure 28. Magnetic probes developed at FEUP. Initial magnetic probe (a) (Nunes, Pimentel and Carvalho, 2016), the new magnetic probe (b).

describes the characteristics of each probe developed at FEUP. According to the inductance measurement of the air in the frequency of 20 Hz, by placing the probes in free air and away from any magnetic objects, it revealed that the inductance of air increased from 14.25 mH to 286 mH for the initial probe (probe 1) to the new developed probe (probe 2), respectively (Nunes and Pimentel, 2016). It is concluded that the inductance measurement by probe 2 is almost 20 times higher than the inductance measurement by the probe 1, which confirms the expectation of the more accurate results being obtained by the new developed version of the probe.

Table 2. Characteristics of the probes developed at FEUP (Nunes, Pimentel and Carvalho, 2016).

Magnetic probes generated in FEUP	Initial probe (Probe 1)	New probe (Probe 2)
Core type	U-shaped ferrite core (Siemens ferrite N47)	
Core length (l_c)	189 mm	
Core section (A_c)	28×30 mm ²	
Copper wire diameter	1 mm	0.5 mm
Number of turns	Unknown	1454
Relative magnetic permeability of core material ($\mu_{r,c}$)	Unknown	

Relative magnetic permeability of the core material ($\mu_{r,c}$) is a significant factor, which is being used in inductance equation. Relative magnetic permeability (μ_r) is the ratio of the permeability of a specific medium (μ) to the permeability of free space (μ_0) (Guru and Hiziroglu, 2012). Moreover, the value of

relative magnetic permeability of the core material ($\mu_{r,c}$) in was unknown ; also in the initial probe, the number of the turns during the fabrication of the probe was not counted. As a result, an experiment was carried out to estimate the value of $N^2\mu_{r,c}$ (N refers to the number of the turns) and consequently, calculate the value of the relative magnetic permeability of the core material ($\mu_{r,c}$).

3.1.2. ESTIMATE OF $N^2\mu_{r,c}$

In a magnetic circuit, the inductance L is defined as the amount of magnetic flux ϕ produced for a given electric current I and is represented in Eq. (1) :

$$L = \frac{\phi}{I} \quad (1)$$

Moreover, the inductance of a simple magnetic circuit shown in Figure 29 (a), which contains a winding with N turns of wire around a core with relative magnetic permeability of $\mu_{r,c}$, is defined by Eq. (2) :

$$L = \frac{\mu_0\mu_{r,c}N^2A_c}{l_m} \quad (2)$$

In which μ_0 is the magnetic permeability of the vacuum, and is defined as $\mu_0=4\pi\times 10^{-7}$ (H/m), l_m is the mean length of the magnetic path and A_c is the cross-sectional area of the core.

This equation confirms that for the fixed core geometry, the amount of inductance and consequently, the magnetic flux is proportional to the relative magnetic permeability of the core material and also to the square of the number of turns around the legs (Nunes, Pimentel and Carvalho, 2016). Furthermore, the electrical equivalent circuit of the Figure 29 (a) (which is presented in Figure 29 (b)) can be based on the Hopkinson's law for magnetic circuits, which expresses that the reluctance of a magnetic circuit (R) is the counterpart of the resistance (R) in electric circuit. Moreover, the magneto-motive force (F_m) is analogous to the electromotive force and the magnetic flux (ϕ) is analogous to the electric current I . Consequently, an equivalent Ohm's law for magnetic circuits is presented in Eq. (3) :

$$\phi = \frac{F_m}{R} = \frac{N \times I}{R} \quad (3)$$

According to equation (3), R is defined as reluctance and is calculated by Eq. (4) :

$$R = \frac{l_m}{\mu_r\mu_0A_c} \quad (4)$$

Taking in to account the equations (2) and (4), the inductance (L) can be evaluated by Eq. (5) :

$$L = \frac{N^2}{R} \quad (5)$$

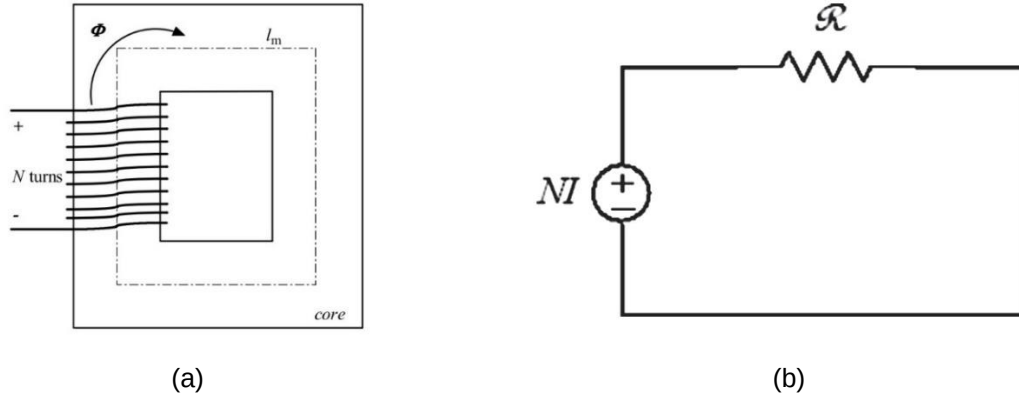


Figure 29. Schematic representation of a magnetic circuit (a), electrical equivalent of the magnetic circuit (b) (Nunes, Pimentel and Carvalho, 2016).

As a result, in order to simulate the magnetic circuit, another U-shaped ferrite magnetic core was placed over the new magnetic probe (see Figure 30). According to the equation (2), the value of $(N^2\mu_{r,c})$ was calculated considering the $A_c = 28 \times 30 \text{ mm}^2$, $l_m = 2 \times 189 \text{ mm}$ (378 mm), and $\mu_0 = 4\pi \times 10^{-7} \text{ (H/m)}$. In the case of new probe that, the number of the turns of the copper wire (N) was known, the relative magnetic permeability of the ferrite core ($\mu_{r,c}$) was calculated; however, it was impossible for the initial probe since the number of the turns of the copper wire was unknown. The result of the relative magnetic permeability of the core is characterized in Table 3.

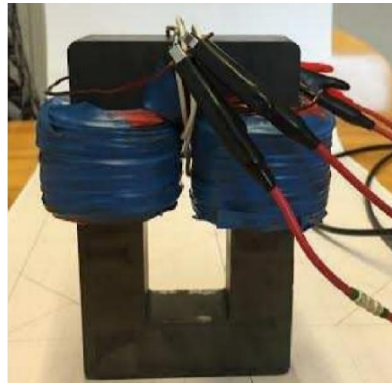


Figure 30. Relative magnetic permeability measuring set-up (Nunes, Pimentel and Carvalho, 2016).

Table 3. Results of the relative magnetic permeability estimation set-up (Nunes, Pimentel and Carvalho, 2016).

Probe	L (H)	$A_c \text{ (m}^2\text{)}$	$L_m \text{ (m)}$	$\mu_{r,c} \cdot N^2$	N	$\mu_{r,c}$
Probe 1	0.268	8.40 E-04	0.378	9.594 E+07	Unknown	—
Probe 2	13.103	8.40 E-04	0.378	4.692 E+09	1454	2219

3.2. THEORETICAL MODEL

An equivalent electrical model for the magnetic circuits, which is based on Hopkinson's law, was used in order to explain how the inductance measurements are affected by changes in fibre content and fibre orientation in UHPFRC. As a result, the UHPFRC layer shown in Figure 27 is represented by a simplified model, which has a 2D distribution of the fibres. Moreover, it was assumed that all the fibres are aligned in the same direction with negligible interaction between them (Nunes, Pimentel and Carvalho, 2016).

3.2.1. FIBRES ALIGNED WITH THE MEASURING DIRECTION ($\theta_i = 0^\circ$)

Firstly, considering a particular case in which all the fibres are aligned with the measuring direction ($\theta_i = 0^\circ$). The UHPFRC layer shown in Figure 27 is illustrated by an equivalent system stating that the whole volume of the fibres are concentrated along the length (l) (Nunes, Pimentel and Carvalho, 2016). See Figure 31.

According to Figure 31 it is assumed that $l_{mp} = l$, $l_{ms} = \gamma l$ and $l_f = (1 - \gamma) l$ in which l_{mp} and l_{ms} are the lengths of the matrix components in parallel and in series with the fibre material, respectively. Additionally, A_{mp} represent the cross section area of the matrix component in parallel with the fibre material, and A_f designates the cross section area of the fibre material. Furthermore, the fibre spacing parameter, which is named as γ , illustrates the space between fibres in θ_i direction.

The corresponding magnetic circuit of the UHPFRC model in Figure 31 is represented in Figure 32. In this figure, R_c , is defined as the reluctance of the core of the magnetic probe, R_f is the magnetic reluctance of the fibres used in the UHPFRC layer, R_{mp} and R_{ms} are the equivalent magnetic reluctances of the matrix components in parallel and in series with the fibre material, respectively.

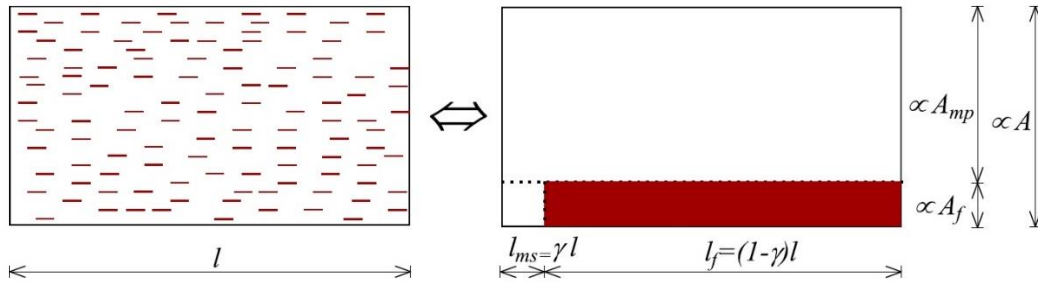


Figure 31. Equivalent model of the UHPFRC layer when all the fibres are aligned with the measuring direction (Nunes, Pimentel and Carvalho, 2016).

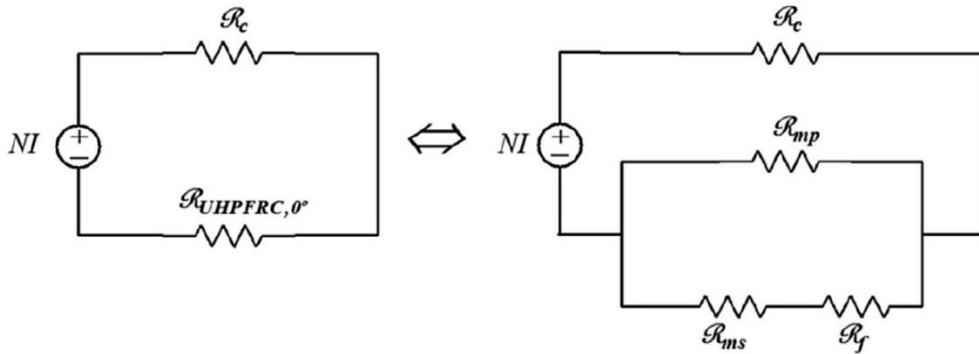


Figure 32. Electrical equivalent model of the magnetic circuit for the fibres aligned with the measuring direction ($\theta_i = 0^\circ$) (Nunes, Pimentel and Carvalho, 2016).

Considering the definition of the reluctance (R) given by equation (4), the total equivalent magnetic reluctance of the circuit (R_{total}) of Figure 32, is defined in Eq. (6) :

$$\begin{aligned} R_{total} &= R_c + [R_{mp} \parallel (R_{ms} + R_f)] \\ &= \frac{l_c}{\mu_0 \cdot \mu_{r,c} \cdot A_c} + \left[\frac{l_{mp}}{\mu_0 \cdot A_{mp}} \parallel \left(\frac{l_{ms}}{\mu_0 \cdot A_{ms}} + \frac{l_f}{\mu_0 \cdot \mu_{r,f} \cdot A_f} \right) \right] \end{aligned} \quad (6)$$

In equation (6), the symbol $\parallel$ defines the association in parallel. Moreover, $\mu_{r,c}$ and $\mu_{r,f}$ refer to the relative magnetic permeability of the core and the fibre materials, respectively. In addition, L_c and A_c refer to the length and cross section area of the core material and A_{ms} is defined as the cross section area of the matrix component in series with the fibre material. The relative magnetic permeability of the matrix is presumed to be the same as the relative magnetic permeability of the air, which is equal to 1 ($\mu_{r,mp} = \mu_{r,ms} = 1$).

The γ parameter would be zero if continuous fibres were used; however, the fibres used in the development of UHPFRC are usually short and discrete ones. Taking into account that in Figure 31, $A_f = A_{ms}$ and the cross-sectional areas can be related to the fibre volume fraction (V_f) by equations (7), and (8) :

$$A_{ms} \cdot l_f = V_f \cdot A \cdot l \Rightarrow A_{ms} = \frac{V_f}{(1 - \gamma)} \cdot A = V_f^* \cdot A \quad (7)$$

$$A_{mp} = A - A_{ms} = (1 - V_f^*) \cdot A \quad (8)$$

In the mentioned equations, A is the total cross-sectional area of the model and V_f is fibre volume fraction. In addition, by replacing the equations (7) and (8) in equation (6), R_{total} for this particular case can be expressed by Eq. (9) as a function of the fibre content (V_f), geometrical (l/A , l_c/A_c), material ($\mu_{r,c}$, $\mu_{r,f}$) and fibre spacing (γ) parameters:

$$\begin{aligned} R_{total} &= \frac{l_c}{\mu_0 \cdot \mu_{r,c} \cdot A_c} + \left[\frac{l}{\mu_0 \cdot (1 - V_f^*) A} \parallel \left(\frac{\gamma l}{\mu_0 \cdot V_f^* \cdot A} + \frac{(1 - \gamma) l}{\mu_0 \cdot \mu_{r,f} \cdot V_f^* \cdot A} \right) \right] \\ &= \frac{l_c}{\mu_0 \cdot \mu_{r,c} \cdot A_c} + \frac{l}{\mu_0 \cdot A} \cdot \frac{\mu_{r,f} \cdot \gamma + 1 - \gamma}{\mu_{r,f} \cdot V_f^* + (1 - V_f^*) \cdot (\mu_{r,f} \cdot \gamma + 1 - \gamma)} \end{aligned} \quad (9)$$

Considering the equation (5), the inductance of this particular case in which, all the fibres are aligned to the measuring direction is estimated by Eq. (10):

$$L_{0^\circ} = \frac{N^2 \mu_0}{\frac{l_c}{\mu_{r,c} \cdot A_c} + \frac{l}{A} \left(\frac{\mu_{r,f} \cdot \gamma + 1 - \gamma}{\mu_{r,f} \cdot V_f^* + (1 - V_f^*) \cdot (\mu_{r,f} \cdot \gamma + 1 - \gamma)} \right)} \quad (10)$$

3.2.2. FIBRES PERPENDICULAR TO THE MEASURING DIRECTION ($\theta_i = 90^\circ$)

In this section the opposite case in which all the fibres are assumed to be perpendicular to the measuring direction ($\theta_i=90^\circ$) is being considered. In this case, the equivalent system considers the concentration of the fibres along the width of the magnetic path. (See Figure 33). In addition, the equivalent electrical model of this specific case is shown in Figure 34 (Nunes, Pimentel and Carvalho, 2016).

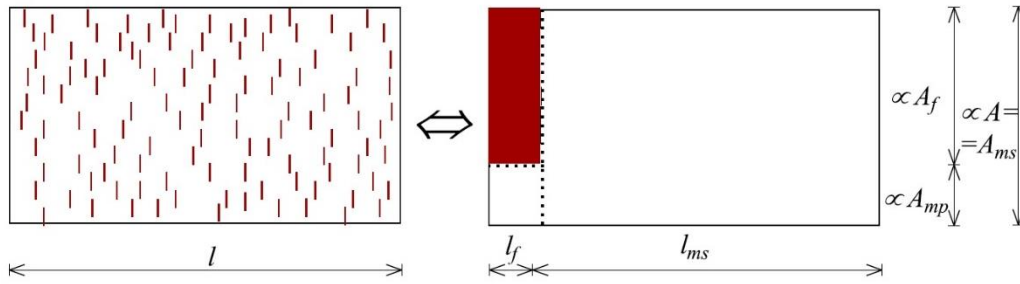


Figure 33. Equivalent model of the UHPFRC layer when all the fibres are perpendicular to the measuring direction (Nunes, Pimentel and Carvalho, 2016).

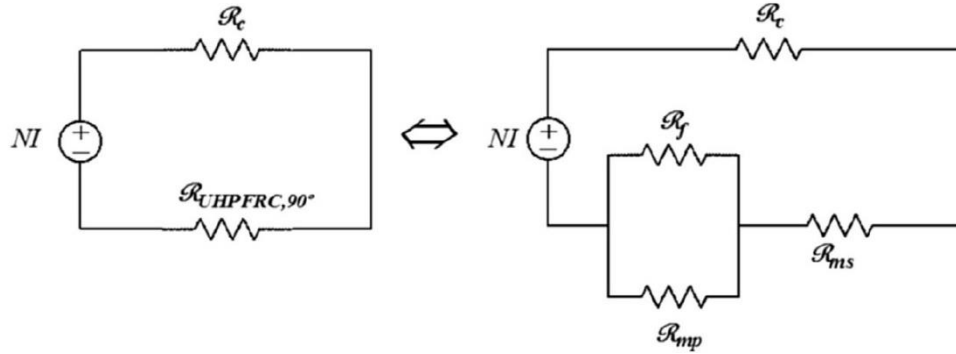


Figure 34. Electrical equivalent model of the magnetic circuit for the fibres perpendicular to the measuring direction ($\theta_i=90^\circ$) (Nunes, Pimentel and Carvalho, 2016).

The total equivalent magnetic reluctance of the circuit (R_{total}) can be calculated by Eq. (11):

$$\begin{aligned} R_{total} &= R_c + (R_f \parallel R_{mp}) + R_{ms} \\ &= \frac{l_c}{\mu_0 \cdot \mu_{r,c} \cdot A_c} + \left(\frac{l_f}{\mu_0 \cdot \mu_{r,f} \cdot A_f} \parallel \frac{l_{mp}}{\mu_0 \cdot A_{mp}} \right) + \frac{l_{ms}}{\mu_0 \cdot A_{ms}} \end{aligned} \quad (11)$$

According to Figure 33, $A_{ms} = A$ and $l_{mp} = l_f$. Taking into account that $A_{mp} = \gamma \cdot A$ and $A_f = (1-\gamma) \cdot A$, the lengths of the magnetic paths is calculated by equations (12) and (13):

$$A_f \cdot l_f = V_f \cdot A \cdot l \Rightarrow l_f = V_f^* \cdot l \quad (12)$$

$$l_{ms} = l - l_f = (1 - V_f^*) \cdot l \quad (13)$$

As a result, R_{total} for this specific case is illustrated in Eq. (14):

$$R_{total} = \frac{l_c}{\mu_0 \cdot \mu_{r,c} \cdot A_c} + \frac{l}{\mu_0 \cdot A} \left[\frac{V_f^*}{\gamma + \mu_{r,f} \cdot (1 - \gamma)} + (1 - V_f^*) \right] \quad (14)$$

Consequently, the inductance (L_{90°) is calculated in Eq. (15):

$$L_{90^\circ} = \frac{N^2 \mu_0}{\frac{l_c}{\mu_{r,c} \cdot A_c} + \frac{l}{A} \left(\frac{V_f^*}{\gamma + \mu_{r,f} \cdot (1 - \gamma)} + 1 - V_f^* \right)} \quad (15)$$

3.2.3. FIBRES FORMING AN ANGLE $0^\circ \leq \theta_i \leq 90^\circ$ WITH THE MEASURING DIRECTION

This section concentrates on a more general case in which all the fibres form an angle $0^\circ \leq \theta_i \leq 90^\circ$ with the measuring direction. In this case, an equivalent system will be considered according to the division of the total volume of the fibres into two parts; first part considering the fibres perpendicular to the measuring direction with the volume fraction of $V_{f1} = V_f \sin^2 \theta_i$; moreover, the second part considering the fibres aligned with the measuring direction with the volume fraction of $V_{f2} = V_f \cos^2 \theta_i$. See Figure 35.

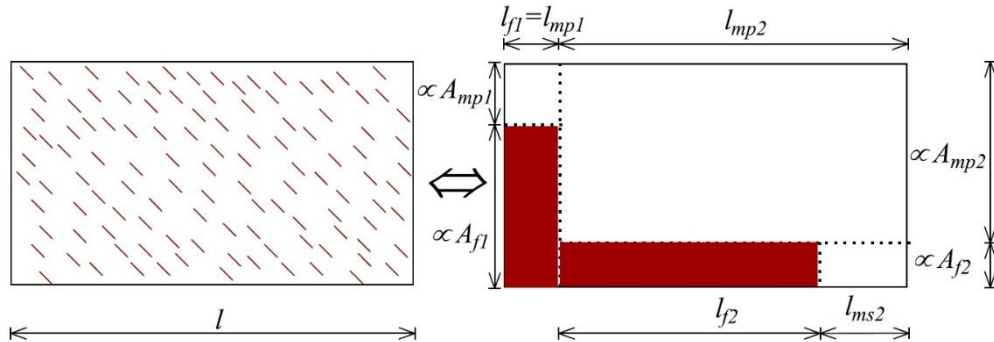


Figure 35. Equivalent model of the UHPFRC layer in general case (Nunes, Pimentel and Carvalho, 2016).

In this case $V_{f1} + V_{f2} = V_f$ and Figure 36 shows the corresponding modelled magnetic circuit. As a result, the total equivalent magnetic reluctance of the circuit R_{total} is presented in Eq. (16):

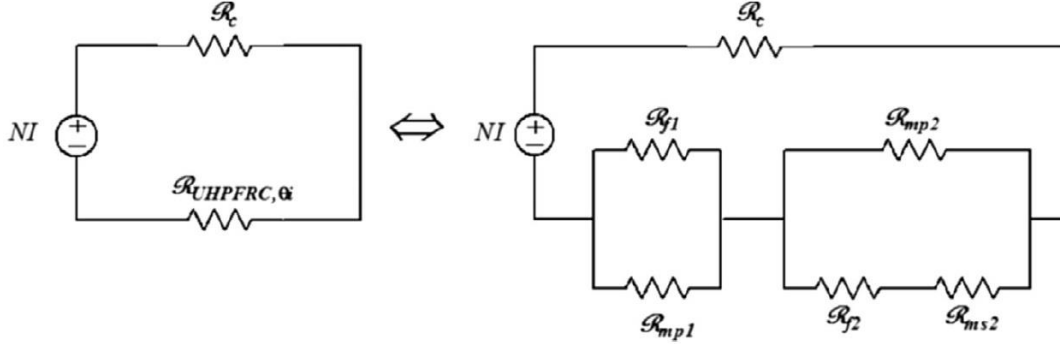


Figure 36. Electrical equivalent model of the magnetic circuit for the fibres in the general case (Nunes, Pimentel and Carvalho, 2016).

$$R_{total} = R_c + (R_{f1} \parallel R_{mp1}) + [R_{mp2} \parallel (R_{f2} + R_{ms2})] \quad (16)$$

The term $(R_{f1} \parallel R_{mp1})$ can be taken from the second part of the equation (11), just replacing V_f by $V_{f1} = V_f \sin^2 \theta_i$. Accordingly, $l_{f1} = l_{mp1} = V_f^* \sin^2 \theta_i \cdot l$, also $l_{mp2} = (1 - V_f^* \sin^2 \theta_i) \cdot l$.

Moreover, the term $[R_{mp2} \parallel (R_{f2} + R_{ms2})]$ can be taken from the second part of the equation (6), replacing the V_f by $V_{f2} = V_f \cos^2 \theta_i$ and l by $l_{mp2} = (1 - V_f^* \sin^2 \theta_i) \cdot l$.

Therefore, the total equivalent magnetic reluctance R_{total} and the inductance $L_{\theta i}$ are shown in equations (17), and (18), respectively.

$$R_{total} = \frac{l_c}{\mu_0 \cdot \mu_{r,c} \cdot A_c} + \frac{l}{\mu_0 \cdot A} \left[\frac{V_f^* \sin^2 \theta_i}{\gamma + \mu_{r,f} \cdot (1 - \gamma)} + \frac{(1 - V_f^* \sin^2 \theta_i) \cdot (\mu_{r,f} \cdot \gamma + 1 - \gamma)}{\mu_{r,f} \cdot V_f^* \cos^2 \theta_i + (1 - V_f^* \cos^2 \theta_i) \cdot (\mu_{r,f} \cdot \gamma + 1 - \gamma)} \right] \quad (17)$$

$$L_{\theta i} = \frac{N^2 \mu_0}{\frac{l_c}{\mu_{r,c} \cdot A_c} + \frac{l}{A} \left(\frac{V_f^* \sin^2 \theta_i}{\gamma + \mu_{r,f} \cdot (1 - \gamma)} + \frac{(1 - V_f^* \sin^2 \theta_i) \cdot (\mu_{r,f} \cdot \gamma + 1 - \gamma)}{\mu_{r,f} \cdot V_f^* \cos^2 \theta_i + (1 - V_f^* \cos^2 \theta_i) \cdot (\mu_{r,f} \cdot \gamma + 1 - \gamma)} \right)} \quad (18)$$

It is concluded that, the inductance measured by the probe placed over a UHPFRC layer, in a giving direction of i depends on specific properties. These properties consist of the core properties, fibre inclination angle θ_i , fibre content (V_f), relative magnetic permeability of the fibre material ($\mu_{r,f}$), number of the turns around the coil (N), spacing parameter (γ), and the geometric factor (l/A).

3.3. FIBRE CONTENT INDICATOR

Relative magnetic permeability of a UHPFRC layer along the direction θ_i (μ_{r,θ_i}), is estimated by dividing the inductance of the UHPFRC layer along the direction θ_i to the inductance of the air (L_{air}). In order to reach to the relative magnetic permeability equation, it is suggested to neglect the contribution of the core in equation (18). Moreover, the inductance of the air is illustrated by $\mu_0 N^2 A/l$. Assuming the shape factor of (l/A) to be constant, the relative magnetic permeability (μ_{r,θ_i}) is defined in Eq. (19):

$$\frac{L_{\theta_i}}{L_{air}} = \frac{1}{\left(\frac{V_f^* \sin^2 \theta_i}{\gamma + \mu_{r,f} \cdot (1 - \gamma)} + \frac{(1 - V_f^* \sin^2 \theta_i) \cdot (\mu_{r,f} \cdot \gamma + 1 - \gamma)}{\mu_{r,f} \cdot V_f^* \cos^2 \theta_i + (1 - V_f^* \cos^2 \theta_i) \cdot (\mu_{r,f} \cdot \gamma + 1 - \gamma)} \right)} \cong \mu_{r,\theta_i} \quad (19)$$

In the same way, replacing θ_i by $(90^\circ - \theta_i)$, and considering the fact that $\sin^2(90^\circ - \theta_i) = \cos^2 \theta_i$, and $\cos^2(90^\circ - \theta_i) = \sin^2 \theta_i$, the relative magnetic permeability along the direction perpendicular to the θ_i direction ($\mu_{r,(90^\circ - \theta_i)}$) is defined by Eq. (20):

$$\frac{L_{(90^\circ - \theta_i)}}{L_{air}} = \frac{1}{\left(\frac{V_f^* \cos^2 \theta_i}{\gamma + \mu_{r,f} \cdot (1 - \gamma)} + \frac{(1 - V_f^* \cos^2 \theta_i) \cdot (\mu_{r,f} \cdot \gamma + 1 - \gamma)}{\mu_{r,f} \cdot V_f^* \sin^2 \theta_i + (1 - V_f^* \sin^2 \theta_i) \cdot (\mu_{r,f} \cdot \gamma + 1 - \gamma)} \right)} \cong \mu_{r,(90^\circ - \theta_i)} \quad (20)$$

The development of (μ_{r,θ_i}) and ($\mu_{r,(90^\circ - \theta_i)}$) as a function of θ_i according to equations (19) and (20) is characterized in Figure 37.

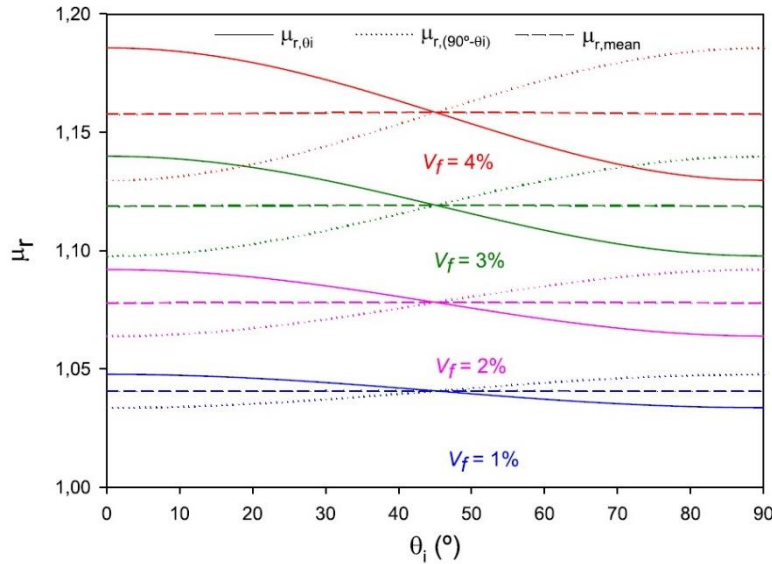


Figure 37. Variation of μ_{r,θ_i} and $\mu_{r,(90^\circ - \theta_i)}$ with the angle θ_i (°) (Nunes, Pimentel and Carvalho, 2016).

According to Figure 37, it is concluded that the relative magnetic permeability of the UHPFRC layer achieves to its maximum value when the fibres are aligned with the measuring direction; however, it

has its minimum value when the fibres are perpendicular to the measuring direction. Moreover, by decreasing $\mu_{r,\theta i}$, the value of $\mu_{r,(90^\circ-\theta i)}$ increases and vice versa.

In addition, for $\theta_i = 45^\circ$, $\mu_{r,\theta i}$ and $\mu_{r,(90^\circ-\theta i)}$ has the same value. The mean value of $\mu_{r,\theta i}$ and $\mu_{r,(90^\circ-\theta i)}$ is given in Eq. (21) and is represented in Figure 37 as well.

$$\mu_{r,mean} = \frac{\mu_{r,\theta i} + \mu_{r,(90^\circ-\theta i)}}{2} \quad (21)$$

As shown in Figure 37, it is proved that $\mu_{r,mean}$ is almost constant for a given fibre content, and does not vary with angle θ_i . Furthermore, it increases linearly by increasing the fibre content. It is worth to mention that mean relative magnetic permeability is independent of the fibre orientation. As a result, $\mu_{r,mean}$ is defined as the fibre content indicator in an UHPFRC layer (Nunes, Pimentel and Carvalho, 2016).

3.4. FIBRE ORIENTATION INDICATOR

Fibre orientation indicator “ $(\rho_{(90^\circ-\theta i)} - \rho_{\theta i})$ (%)” is defined for recognizing the preferential orientation of the fibres in UHPFRC layers. Due to the presence of the fibres in UHPFRC layers, the increase of μ_r is calculated in Eq. (22) for any two perpendicular directions:

$$\Delta\mu_{r,\theta i} = \mu_{r,\theta i} - 1 \quad (22)$$

Afterwards the relative increase of μ_r in each direction can be evaluated in Eq. (23):

$$\rho_{\theta i} = \frac{\Delta\mu_{r,\theta i}}{\Delta\mu_{r,\theta i} + \Delta\mu_{r,(90^\circ-\theta i)}} ; \quad \rho_{(90^\circ-\theta i)} = \frac{\Delta\mu_{r,(90^\circ-\theta i)}}{\Delta\mu_{r,\theta i} + \Delta\mu_{r,(90^\circ-\theta i)}} \quad (23)$$

According to equation (23) the difference $(\rho_{(90^\circ-\theta i)} - \rho_{\theta i})$ is calculated in equations (24) and (25) (Nunes, Pimentel and Carvalho, 2016):

$$\begin{aligned} \rho_{(90^\circ-\theta i)} - \rho_{\theta i} &= \frac{\Delta\mu_{r,(90^\circ-\theta i)} - \Delta\mu_{r,\theta i}}{\Delta\mu_{r,\theta i} + \Delta\mu_{r,(90^\circ-\theta i)}} \\ &= \frac{\mu_{r,(90^\circ-\theta i)} - 1 - (\mu_{r,\theta i} - 1)}{\mu_{r,\theta i} - 1 + \mu_{r,(90^\circ-\theta i)} - 1} \end{aligned} \quad (24)$$

$$\rho_{(90^\circ-\theta_i)} - \rho_{\theta_i} = \frac{\mu_{r,(90^\circ-\theta_i)} - \mu_{r,\theta_i}}{2(\mu_{r,mean} - 1)} \quad (25)$$

The fibre orientation indicator is represented in Figure 38 for different fibre contents as a function of angle θ_i .

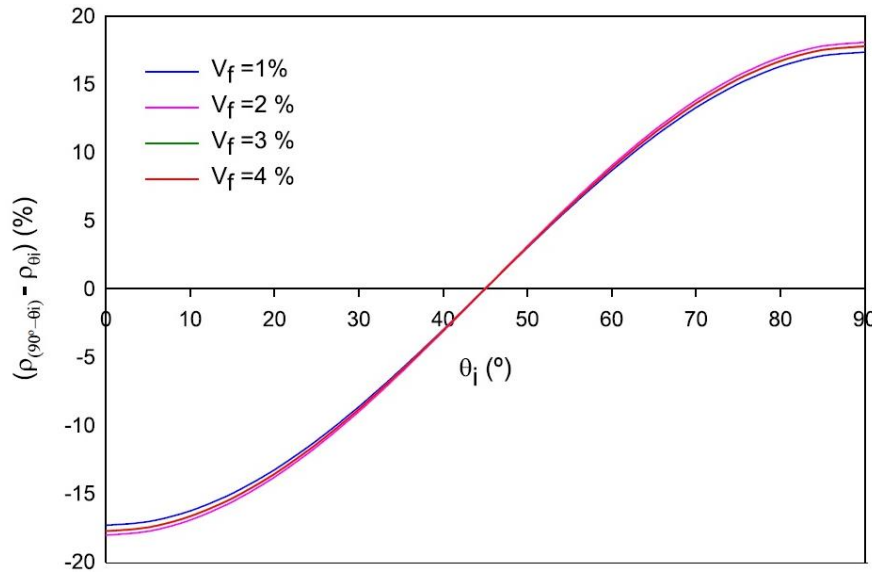


Figure 38. Variation of $(\rho_{(90^\circ-\theta_i)} - \rho_{\theta_i})$ with angle θ_i for different fibre contents (Nunes, Pimentel and Carvalho, 2016).

According to Figure 38 and keeping the equation (25) in mind, it is clarified that the positive values of fibre orientation factor indicate the orientation of the fibres perpendicular to i direction while the negative values proves the orientation of the fibres along i direction. Moreover, the results close to zero indicate no preferential direction (called random), or it can also be a measurement at 45° with respect to the direction of maximum fibre orientation. As an important point, it can be observed that the fibre orientation factor is independent from the fibre content.

The tensile response of an UHPFRC layer is highly effected by the fibre content and fibre orientation indicators, consequently these indicators play an important role in the estimation of the tensile response of the material.

3.5. CONCLUSIONS

- The proposed NDT method for the detection of fibre content and fibre orientation indicator can be applied for quality control of UHPFRC structures both in the laboratory and in the worksite.
- According to the theoretical model, based on the analogy between the magnetic and electric circuits some equations were derived for estimating the magnetic inductance. Consequently, two reliable indicators of fibre content and fibre orientation were developed.

- The average of two relative magnetic permeability results in two perpendicular directions ($\mu_{r,\text{mean}}$) increases with the fibre content and is independent of fibre orientation.
- The fibre orientation indicator in order to define the preferential orientation of the fibres can be calculated by the results of relative magnetic permeability in two perpendicular directions and is independent of fibre content.

4

TEST PROGRAMME 1: SMALL CUBIC SPECIMENS

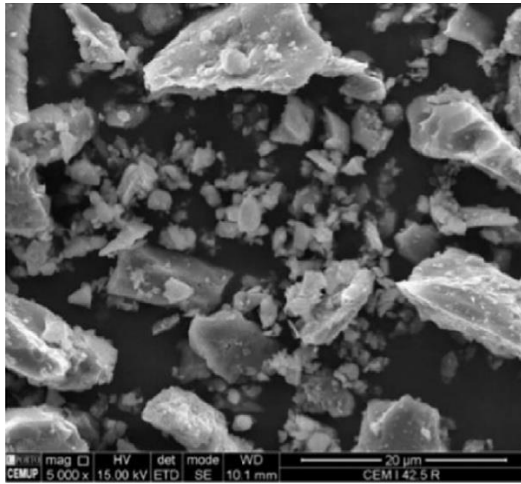
4.1. OBJECTIVES

As discussed in the previous chapters, recently many researchers have focused on experiments done on UHPFRCs (Ultra-high performance fibre reinforced cementitious composites). The main purpose of these experiments is to reach to unique fibre content and fibre orientation indicators by measuring the inductance (L) only in two perpendicular directions of X and Y (Nunes, Pimentel and Carvalho, 2016). As it is obvious, in the previous works, measurements on the third direction were neglected, due to the fact that, the measurements were applied on thin layers of UHPFRCs with the length and width much higher than the thickness. As a result, it was almost impossible to get the inductance of the third direction in all points of the element, without cutting the specimen. Therefore, a simplified campaign consisting of specimens with the same dimensions in all surfaces were designed in order to get the inductance of the third direction as well. However, this simplification and consequently the results are reasonable either when the specimens are small enough that there is no need to be cut, or the dimensions of the specimens are the same as the dimensions of the cross section area of the probe used in the test (not bigger than the probe). So that the specimens can be placed properly in between the probes.

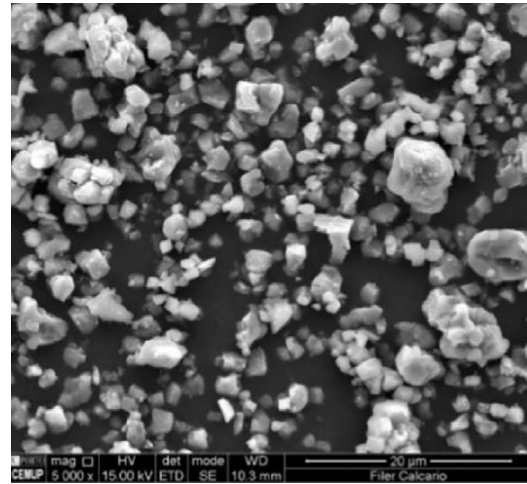
Therefore, this chapter considers primarily doing the measurements and getting the results in all three directions of X, Y and Z, by using NDT method described in Chapter 3, without any need to extract core samples. Moreover, the second objective of this particular experimental campaign is to define reliable fibre content, and fibre orientation indicator, which can be used in alternative specimens with unknown amounts of fibres. Hence, the tests were carried out on small cubic specimens of $30 \times 30 \times 30 \text{ mm}^3$, which facilitate measuring the inductance in all three directions. Two different types of oriented (O) and random (R) specimens with distinctive fibre volume fractions of 1%, 2%, 3%, and 4% were tested. In addition, for each fibre dosage, 6 specimens were used. All details about the present work are described in the following sections.

4.2. MATERIALS AND MIXTURE PROPORTIONS

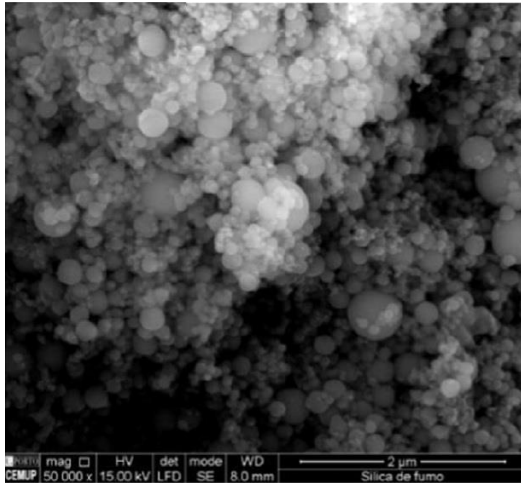
Materials used for the mixtures in the present work consist of cement type (I) with the strength class of 42.5 R, limestone filler, and silica fume with the specific gravity of 3.10, 2.68 and 1.38, respectively. Moreover, the average particle size of the incorporated cement and limestone filler is 14.6 and 5.36 μm , respectively. See Figure 39 (a), (b), and (c). The superplasticizer, used in the matrix consists of, reformed carboxylates with the specific gravity of 1.08 and 40% solid content. Fine aggregate of sand used in the mixture, has the specific gravity of 2.63 (dry material) and 0.3% absorption (Abrishambaf, Pimentel and Nunes, 2017). In this mixture, the straight micro steel fibres of Krampharex with the length of 6 mm and cross section diameter of 0.175 mm were used. The fibres have the tensile strength of 2100 MPa, with the aspect ratio (l/d_f) of 34. See Figure 39 (d).



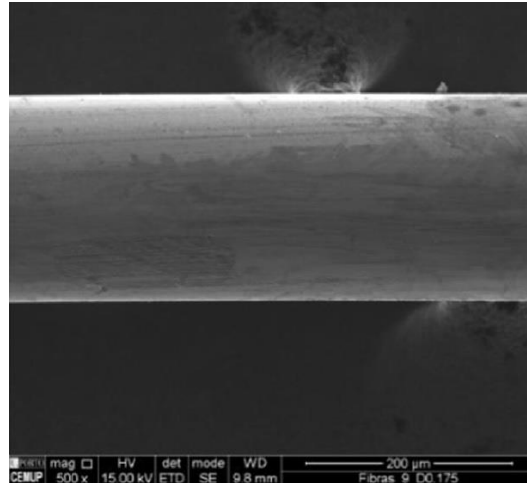
(a)



(b)



(c)



(d)

Figure 39. Particle structures of cement (a), limestone filler (b), silica fume (c), and fibre (d) (Abrishambaf, Pimentel and Nunes, 2017).

In addition to the microscopic figures presented previously, Figure 40 illustrates the general features of the materials used in the laboratory.



Figure 40. Straight Krampharex fibres with 6 mm length and cross section diameter of 0.175 mm (a). All the material used in the mixture (b).

As mentioned before, for the mixture to be flowable and homogenous, an appropriate proportion of the materials has to be mixed. These proportions are characterized precisely in Table 4. Each mix in the table describes the fibre dosage used in, as an example; Mix 1, refers to the mixture with 1% of fibre content. Moreover, each mix was prepared for the volume of 1.4 litter. It is worth to mention that, by increasing the volume of the fibres, the amount of fine aggregates decreases in order to keep the balance. Meanwhile, the amount of all the other materials remains constant. It is a significant point, since any small changes in the proportions, can lead to deficiency in the mortar and consequently in the workability of the concrete (E.Fehling, [s.d.]).

Table 4. Proportion of the materials used in the mixture (kg/m^3).

Constituent	Mix 1	Mix 2	Mix 3	Mix 4
Cement	794.9	794.9	794.9	794.9
Silica fume	79.49	79.49	79.49	79.49
Limestone filler	311.43	311.43	311.43	311.43
Sand	993.562	967.262	940.962	914.662
Water	145.36	145.36	145.36	145.36
Superplasticizer	30	30	30	30
Fibres (volume fraction)	78.5 (1%)	157 (2%)	235.5 (3%)	314 (4%)

4.3. MIXING, CASTING AND PREPARATION OF THE SPECIMENS

4.3.1. MIXING PROCEDURE

The mixing process is described in detail in Table 5 (Nunes, Pimentel and Carvalho, 2016). A significant point of this process and mixture is the last step of adding fibres. In order to guarantee a good dispersion of the fibres, for dosages of 3%, and 4% (higher amounts of fibres), the last task of adding fibres was divided in to two steps. This means that half of the fibres were added, and mixed for 1 minute, then the

other half was added, and mixed for another 1 minute. Figure 41 represents the stage of adding superplasticizer to the mixture. At the end of the mixing, slump flow test was carried out, in order to check its flowability.

Table 5. Mixing procedure (Nunes, Pimentel and Carvalho, 2016).

Task	Duration
Mix sand, cement, limestone filler, silica fume, and 80% of water	2.5min + * + 2.5min
Add 20% of water and 75% of superplasticizer	2.5min + *
Add 25% of superplasticizer	1.5min
Add fibres	2min

(*) Stoppage to scrape material into the mixing bowl.



Figure 41. Mixing process in the stage of adding superplasticizer

4.3.2. FRESH STATE CHARACTERIZATION

Immediately after having the mortar ready, the slump flow test was done, in order to check its flowability. According to EFNARC (European Federation of National Associations Representing producers and applicators of specialist building products for Concrete) recommendations, a mini-cone was used for measuring the slump-flow diameter. In the slump flow test, two perpendicular diameters of the spread area of the mix were measured, and flow diameter results were calculated by the mean value of two diameters. In regarding to the low water/binder (w/b) ratio and very high content of fine materials, the mixture shows a very high viscosity with very low risk of segregation. As a result, no extra tests applied for characterizing fresh state (Matos *et al.*, 2019). Figure 42 (a), (b) presents the process of slump flow test.

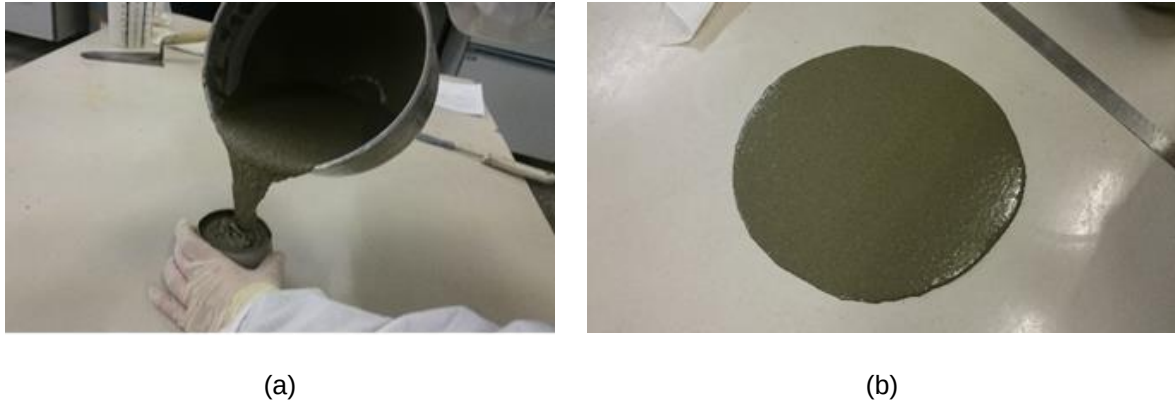


Figure 42. Procedure of slump flow test done (a), and (b).

4.3.3. SPECIMEN PREPARATION

After slump flow test done, random and oriented specimens were cast. Firstly, started with the random specimens, which were easier. Simply by placing the material in the mould. The point, which had to be taken in to account, was the mould used for random specimens. The mould was a prism consisting of separated spaces for casting; however, for oriented specimens the mould was a straight prism without any spaces inside. The final feature is shown in Figure 43 (a) for random specimens after casting and Figure 43 (b) after demoulding the specimens 24 hours after casting.

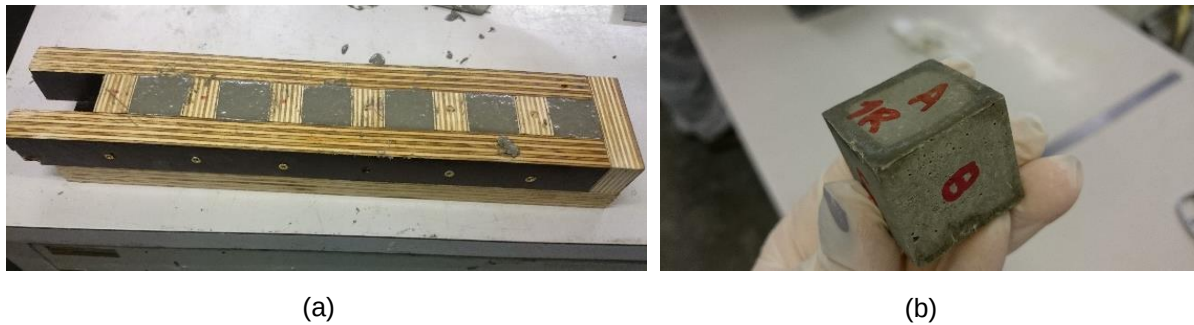


Figure 43. Random specimens after casting (a). Random specimens after demoulding (b).

For the other group of specimens (Oriented specimens), casting procedure was the same; however, it was performed inside an orientation set-up. The role of this set-up is to generate an electromagnetic field, which is capable of orienting and aligning the fibres along a particular pre-established direction (Nunes *et al.*, 2017). The set-up consists of a U-shaped iron, with copper winding on its legs similar to the one used in the probe, but in a large scale. The number of turns is 850, and the set-up is powered by a 12 V battery, with a current intensity of 2 A. When the current passes through the windings, it creates a magnetic field, which develops the north, and south poles on its each leg; furthermore, it forces the fibres to be aligned along the direction of its field lines. The estimated magnetic flux would be 1.88×10^5 Wb, in addition to the magnetic flux density of 5.01×10^{-3} T, through the empty mould placed inside the set-up. Based on the aforementioned data, the mould was kept inside the magnetic field during casting (Nunes, Pimentel and Carvalho, 2016). As a result, the fibres were forced to be oriented in a preferential direction, which was along the lines of the electromagnetic field, and named as X direction or 0° . Correspondingly, these specimens were referenced as “oriented specimens”. In order to assure

the good orientation of the fibres, it is suggested to keep the magnetic field after casting for about 6-7 hours. Figure 44 designates the process of casting oriented specimens inside the fibre orientation set-up and Figure 45 shows the specimen after casting inside the fibre orientation set-up. It is worth to mention that, for the fibre dosages of 3%, and 4%, a more powerful magnetic field is needed, since high amounts of fibres will increase the resistance against movements. Therefore, the power of the field has to be increased in order to be capable of orienting, and aligning all the fibres.



Figure 44. Casting oriented specimens inside fibre orientation set-up.

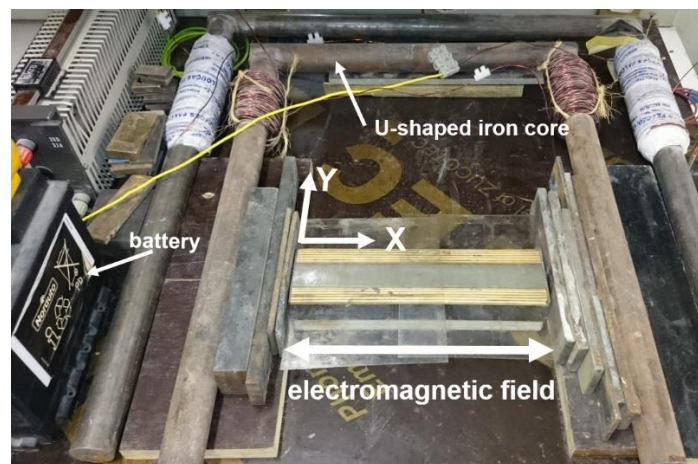


Figure 45. Oriented specimen after casting kept inside the fibre orientation set-up.

The specimens were demoulded 24 hours after casting. After demoulding, oriented specimens were cut in to small cubes of $30 \times 30 \times 30 \text{ mm}^3$ by using a blade with the thickness of 3mm. See Figure 46.



Figure 46. Oriented specimens after cutting.

As it is obvious, there are a large number of specimens, 12 specimens for each fibre dosage including random, and oriented, which means 48 specimens in total. Therefore, the specimens were referenced precisely, in order not to lose the track of them. See Table 6. As it is shown, the specimens were referenced with the letters of “R” for random and “O” for the oriented ones. Moreover, the specimens were numbered from 1 to 6, randomly in random specimens, and in a well-organized way (from left to right) in oriented specimens, which is presented in . The letter A is referred to Z direction, or the casting direction, B is related to X axis, or the axis that the fibres are oriented (0°), and C is called for the last remaining direction, or Y axis. See . The reference chosen for the couples of the specimens that used in the set-up was (1, 6), (2, 5), and (3, 4). See Figure 49 .The main purpose of this order was to reduce the errors, and increase the accuracy of the results by choosing the specimens having the same conditions during casting. These conditions refer to the wall-effect and their distance from the start point of the magnetic field. In addition, the specimens and test conditions are referenced in Table 7. In the mentioned table; OA 1% (1, 6), (2, 5), (3, 4), designates the measurements on oriented specimens of groups of (1, 6), (2, 5), and (3, 4) with 1% of fibre content in which the test is done on A (Z) surface.

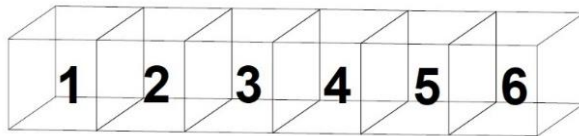


Figure 47. Numbering oriented specimens from left to right.

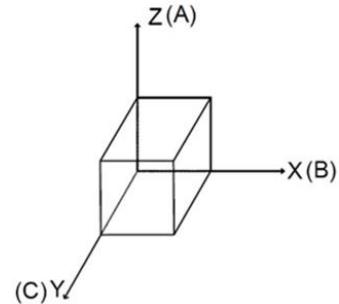


Figure 48. Reference of directions in cubes.

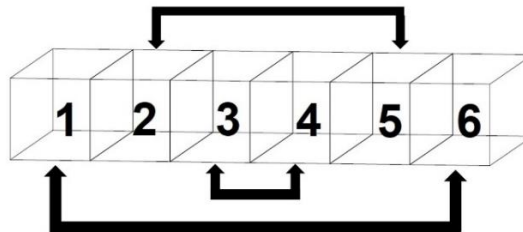


Figure 49. Preferential order for measurements in oriented specimens.

Table 6. General reference of the campaign and specimens.

Fibre orientation	Fibre content	Surface reference	Specimen reference
Oriented along X direction (O)	1%	A	OA 1%
		B	OB 1%
		C	OC 1%
	2%	A	OA 2%
		B	OB 2%
		C	OC 2%
	3%	A	OA 3%
		B	OB 3%
		C	OC 3%
	4%	A	OA 4%
		B	OB 4%
		C	OC 4%
Random (R)	1%	A	RA 1%
		B	RB 1%
		C	RC 1%
	2%	A	RA 2%
		B	RB 2%
		C	RC 2%
	3%	A	RA 3%
		B	RB 3%
		C	RC 3%
	4%	A	RA 4%
		B	RB 4%
		C	RC 4%

Table 7. Specimens and test conditions' reference.

Fibre orientation	Fibre content	Test conditions
Oriented along X direction (O)	1%	OA 1% (1, 6),(2, 5),(3, 4)
		OB 1% (1, 6),(2, 5),(3, 4)
		OC 1% (1, 6),(2, 5),(3, 4)
	2%	OA 2% (1, 6),(2, 5),(3, 4)
		OB 2% (1, 6),(2, 5),(3, 4)
		OC 2% (1, 6),(2, 5),(3, 4)
	3%	OA 3% (1, 6),(2, 5),(3, 4)
		OB 3% (1, 6),(2, 5),(3, 4)
		OC 3% (1, 6),(2, 5),(3, 4)
	4%	OA 4% (1, 6),(2, 5),(3, 4)
		OB 4% (1, 6),(2, 5),(3, 4)
		OC 4% (1, 6),(2, 5),(3, 4)
Random (R)	1%	RA 1% (1, 6),(2, 5),(3, 4)
		RB 1% (1, 6),(2, 5),(3, 4)
		RC 1% (1, 6),(2, 5),(3, 4)
	2%	RA 2% (1, 6),(2, 5),(3, 4)
		RB 2% (1, 6),(2, 5),(3, 4)
		RC 2% (1, 6),(2, 5),(3, 4)
	3%	RA 3% (1, 6),(2, 5),(3, 4)
		RB 3% (1, 6),(2, 5),(3, 4)
		RC 3% (1, 6),(2, 5),(3, 4)
	4%	RA 4% (1, 6),(2, 5),(3, 4)
		RB 4% (1, 6),(2, 5),(3, 4)
		RC 4% (1, 6),(2, 5),(3, 4)

4.4. INDUCTANCE MEASUREMENTS

Inductance measurements were done by using a high-precision Agilent E4980A LCR meter (Nunes, Pimentel and Carvalho, 2016). The process of measuring inductance was by placing 2 cubic specimens of the same group and number discussed previously in detail in Table 7, in between two probes regarding to the desired surface. See Figure 50 (a). In addition, only one of the probes was connected to the LCR meter and the data was saved on a pen drive connected to LCR meter. Moreover, the function of the second probe was to complete the electromagnetic field path in the set-up. Furthermore, for

measuring the inductance in each direction (A, B, and C) the specimens were rotated and were put according to the desired surface in between the probes.

Another point that had to be taken in to consideration was the procedure used for measuring the inductance of air. In this case, cubes of $30 \times 30 \times 30 \text{ mm}^3$ that are made of a material, with the conductivity properties of zero, placed in between the probes. See Figure 50 (b). It is notable that in all the measurements the test frequency was 20 Hz, with the signal level of 2 V (AC current). In order to guarantee the reliability of the results, all the measurements were taken away from any other ferromagnetic objects (Nunes, Pimentel and Carvalho, 2016).



Figure 50. Inductance measurements in cubes (a). Inductance measurement of air (L_{air}) (b).

4.5. RESULTS AND ANALYSIS

4.5.1. FRESH STATE RESULTS

Fresh state results related to the slump flow test done in 4.3.2, are presented in Table 8. As it is obvious, the results of the third casting is not acceptable, because of the poor flowability. The reason of this phenomenon was using a new packet of cement in this casting. Therefore, Mix 3 was repeated with the same cement used in the previous castings. As conclusion, all the mixtures show a very close average flow diameter.

Table 8. Slump-flow test results.

Mixture	Mix 1	Mix 2	Mix 3	Mix 3	Mix 4
Date of casting	13/02/2019	14/02/2019	15/02/2019	18/02/2019 (Repeated)	19/02/2019
D1 (mm)	295	296	243	301	275
D2 (mm)	293	297	256	308	286
Average diameter(mm)	294	296.5	249.5	304.5	280.5

4.5.2. INDUCTANCE RESULTS IN EACH DIRECTION: L_x , L_y , L_z

Inductance results from the measurements according to the process explained in 4.4, are summarized in detail in Table 9 for random and in

Table 10 for oriented specimens. The tables reveal measurements in 3 orthogonal directions.

Table 9. Inductance results for random specimens.

Random	Specimens' reference	L_z (mH)	L_x (mH)	L_y (mH)	Average (mH)
1%	R 1% (1, 6)	300.2	302.4	304.5	302.3
	R 1% (2, 5)	300.3	304.3	302.5	302.4
	R 1% (3, 4)	301.9	303.1	302.3	302.4
	Air		296.5		
2%	R 2% (1, 6)	307.2	306.1	311.8	308.4
	R 2% (2, 5)	306.3	309.0	309.6	308.3
	R 2% (3, 4)	305.7	307.4	311.4	308.2
	Air		296.5		
3%	R 3% (1, 6)	310.9	312.7	316.2	313.3
	R 3% (2, 5)	310.8	317.9	312.3	313.7
	R 3% (3, 4)	312.3	311.7	316.9	313.6
	Air		296.5		
4%	R 4% (1, 6)	310.7	319.7	319.7	316.7
	R 4% (2, 5)	311.5	316.4	323.8	317.2
	R 4% (3, 4)	313.5	314.5	325.4	317.8
	Air		296.5		

As can be observed in Table 9, inductance results in all directions in random specimens are almost same and very close to each other. It was expected since there was not a preferential orientation in the specimens during casting.

Table 10. Inductance results for oriented specimens.

Oriented	Specimens' reference	L_z (mH)	L_x (mH)	L_y (mH)	Average (mH)
1%	O 1% (1, 6)	299.0	312.2	299.3	303.5
	O 1% (2, 5)	298.6	311.9	299.1	303.2
	O 1% (3, 4)	298.8	311.9	299.6	303.4
	Air		296.5		
2%	O 2% (1, 6)	301.5	323.1	303.7	309.4
	O 2% (2, 5)	300.8	324.6	302.9	309.4
	O 2% (3, 4)	301.2	321.8	303.0	308.7
	Air		296.5		
3%	O 3% (1, 6)	302.3	333.3	307.0	314.2
	O 3% (2, 5)	301.8	335.1	305.3	314.1
	O 3% (3, 4)	302.0	334.6	305.9	314.2
	Air		296.5		
4%	O 4% (1, 6)	305.3	344.8	310.0	320.0
	O 4% (2, 5)	304.5	348.4	308.9	320.6
	O 4% (3, 4)	303.5	348.3	308.3	320.0
	Air		296.5		

As an obvious point of these results, is the noticeable difference of L_x in oriented specimens in comparison with L_z , and L_y . It was expected since the specimens were oriented along X direction.

Mean inductance results in random, and oriented specimens are compared in two different perpendicular directions, and are presented in detail in Figure 51. In order to better clarify the results, a line of 45°, which passes through the origin of the graph, is used.

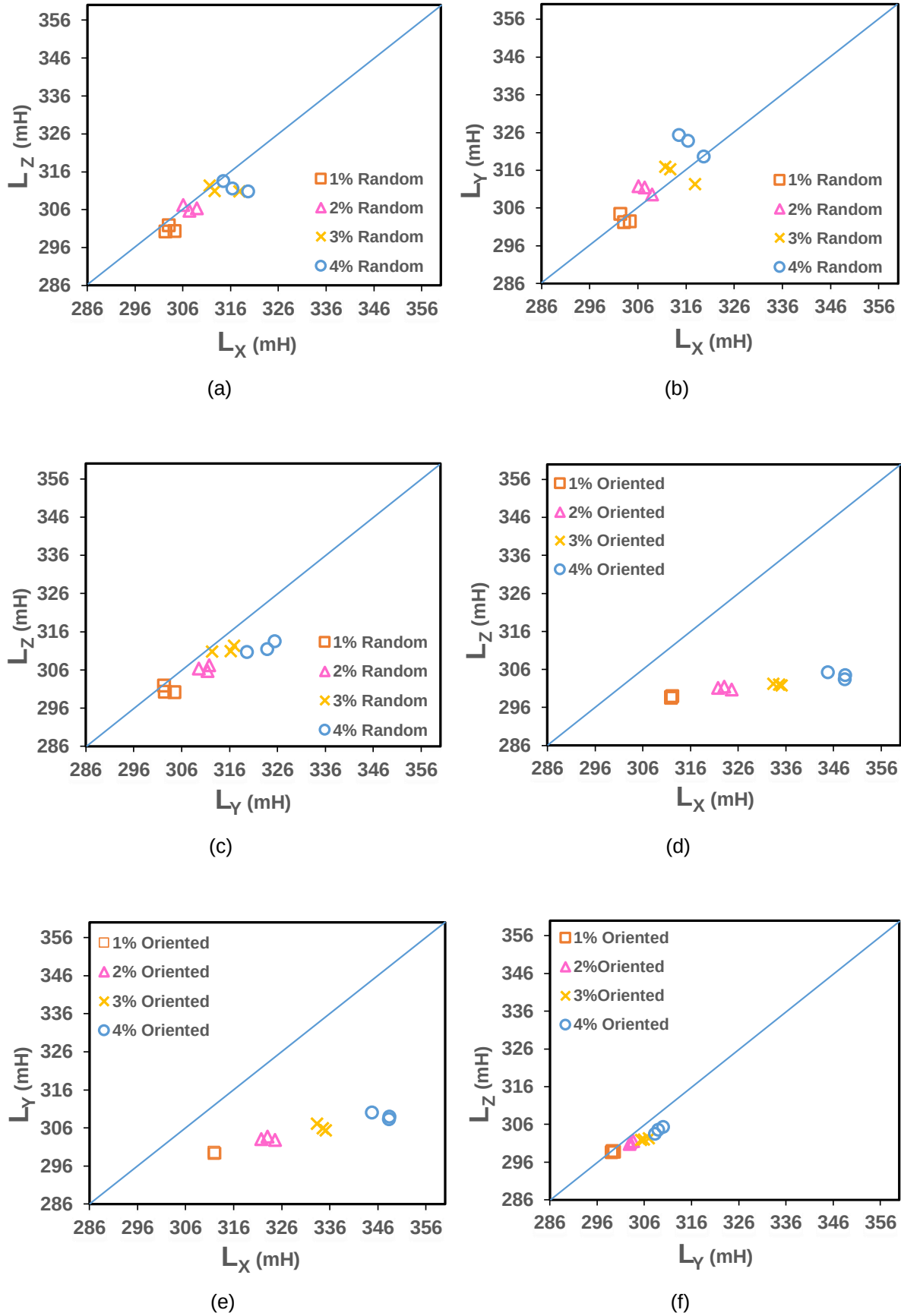


Figure 51. Mean inductance results in two perpendicular directions in random specimens (a), (b), and (c). In oriented specimens (d), (e), and (f).

According to Figure 51, it is concluded that in random specimens the results in all directions are almost around and close to the line of 45°. This means, the results in all directions are close to each other, and the variation is low, as expected for random specimens. Furthermore, in oriented specimens the inductance results are more close and aligned toward the X-axis. This means that specimens are aligned along X direction. Nevertheless, the results in the other two directions are close to the line of 45°. These conclusions are as a proof for the accuracy of the specimens, which were oriented in X direction. Moreover, in Figure 51 (b), and (c), for random specimens with the fibre content of 4%, a slight orientation in Y direction can be observed. This phenomenon can be justified due to the wall effect, in which fibres orient parallel to the moulded surface.

4.5.3. FIBRE CONTENT INDICATOR

According to the results of the previous research by S. Nunes, M. Pimentel, A. Carvalho (2016), and explained in chapter 3 section (3.3) it was represented that the relative magnetic permeability of UHPFRC along a defined direction of θ_i (μ_{r,θ_i}), can be estimated approximately using Eq. (26):

$$\mu_{r,\theta_i} \cong \frac{L_{\theta_i}}{L_{air}} \quad (26)$$

As a result, by developing equation (26), the mean relative magnetic permeability in the present campaign of specimens can be calculated by Eq. (27):

$$\mu_{r,mean} = \frac{\mu_{r,x} + \mu_{r,y} + \mu_{r,z}}{3} \quad (27)$$

Additionally, the results of mean relative magnetic permeability ($\mu_{r,mean}$) are represented as a function of fibre content in Figure 52 (a) for random, and (b) for oriented specimens.

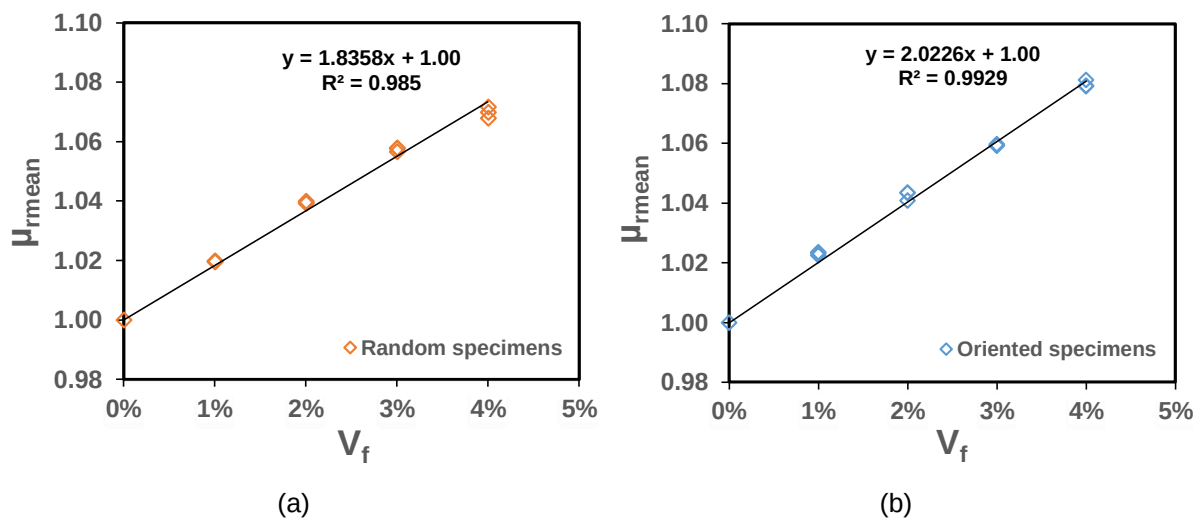


Figure 52. Mean relative magnetic permeability in random specimens (a), and oriented specimens (b).

It can be concluded that there is a linear relation between the mean relative magnetic permeability results ($\mu_{r,mean}$) and fibre content in all specimens. This means by increasing the fibre dosage the mean relative magnetic permeability ($\mu_{r,mean}$) is increasing linearly. In the previous work of S. Nunes, M. Pimentel, A. Carvalho (2016) it was proved that $\mu_{r,mean}$ is almost constant for a given fibre dosage and is increasing linearly in proportion with the increase of the fibre content. The fibre content indicator in both series of specimens, i.e. random and oriented, is characterized in Figure 53. As it is shown, fibre content indicator is slightly higher in oriented specimens than in random specimens.

To better understand the reason, fibre content indicator is characterized neglecting the specimens with 4% of fibre content (due to low workability). See Figure 54, which indicates almost similar fibre content indicator factor for all specimens.

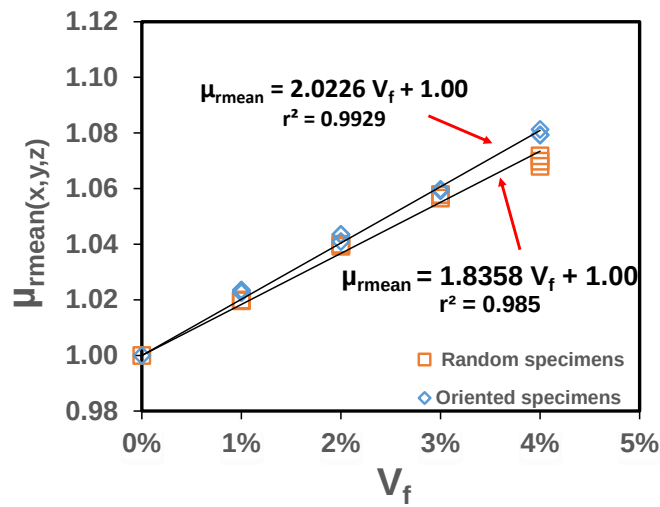


Figure 53. Fibre content indicator in random and oriented specimens.

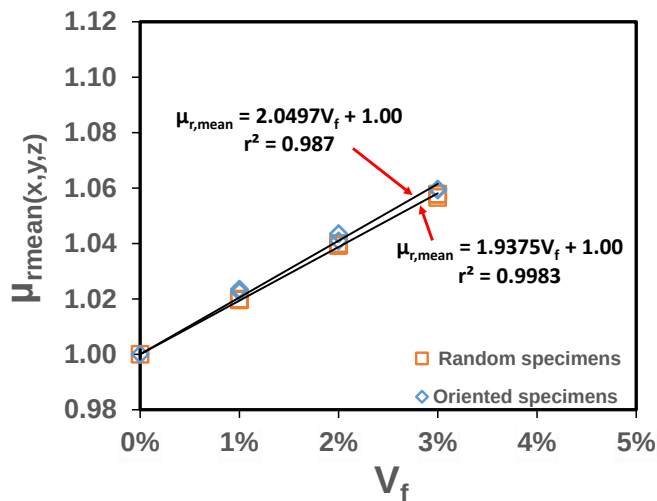


Figure 54. Fibre content indicator neglecting 4% fibre content.

In order to better qualify the third direction measurements effect, the fitting lines were obtained using only the results of directions X and Y (2D) in both random, and oriented specimens (see Figure 55).

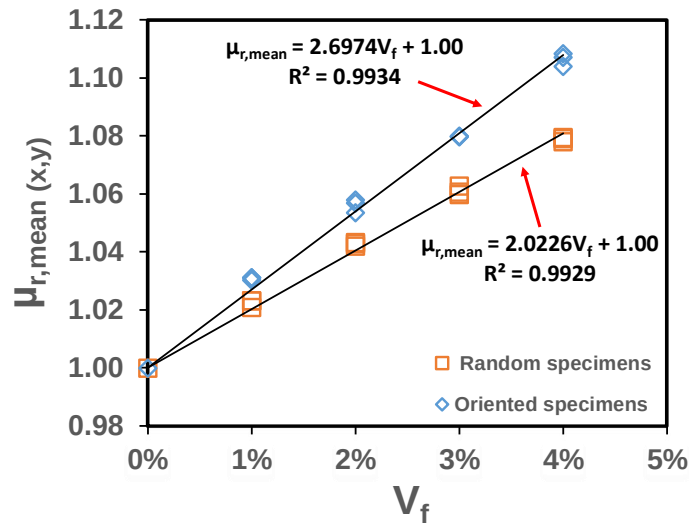


Figure 55. Fibre content indicator factor for random and oriented specimens calculated only for X, and Y direction (2D).

Moreover, Figure 56 compares the fibre content indicator factor using the measurements in all three directions and only the measurements on X and Y directions. It is concluded that in 2D measurements $\mu_{r,mean}$ has increased in both oriented and random specimens.

This phenomenon is accepted for oriented specimens since $\mu_{r,x}$ is larger than $\mu_{r,y}$, and $\mu_{r,z}$. However, in random specimens theoretically for 2D and 3D measurements, it is expected to get almost similar fibre content indicator results according to the equation (27).

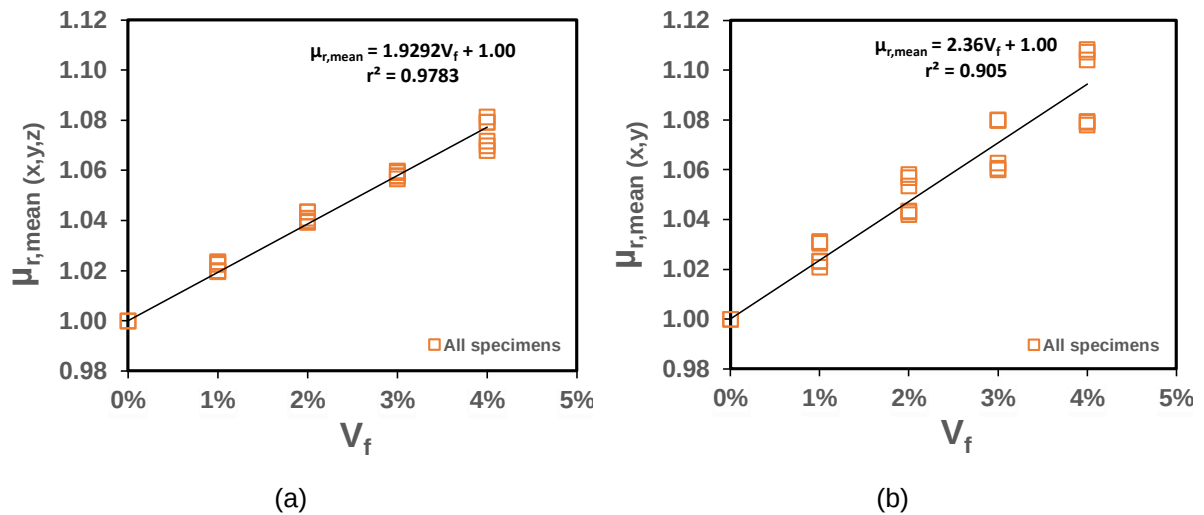


Figure 56. Fibre content indicator in all specimens regarding to 3D measurements (a), and 2D measurements (b).

4.5.4. FIBRE ORIENTATION INDICATOR

Fibre orientation factor “ $(\rho_i - \rho_j) (\%)$ ” is calculated according to Eq. (28) in which i and j represent two perpendicular directions, as discussed previously in chapter 3:

$$\rho_i - \rho_j = \frac{\mu_{r,i} - \mu_{r,j}}{2(\mu_{r,mean} - 1)} \quad (28)$$

The results of the fibre orientation factor are presented in Figure 57 (a) for random specimens and (b) for oriented specimens.

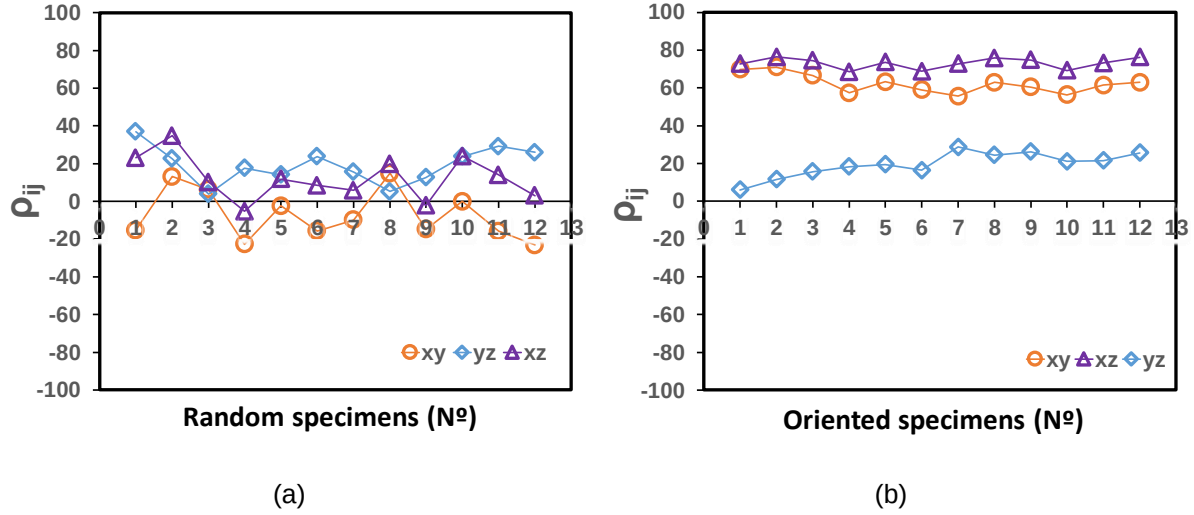


Figure 57. Fibre orientation indicator in random specimens (a), and oriented specimens (b).

According to the equation (28), when fibre orientation indicator is positive it designates $\mu_{r,x} > \mu_{r,y}$, which means that the fibres are oriented in X direction. On the other hand if ρ_{xy} is negative, it means that $\mu_{r,x} < \mu_{r,y}$, and fibres are oriented in Y direction; moreover, if the result is 0, there is no preferential orientation of the fibres, which is named as random. Consequently, in Figure 57 for random specimens some orientations can be observed. In oriented specimens, the results of ρ_{xy} and ρ_{xz} designate that specimens have higher mean magnetic permeability in X direction than Y, and Z direction, as it was expected to be.

However, according to the result of ρ_{yz} in random specimens, some slight orientations can be observed in Y direction. This can be due to the fact that in Z direction, the measurements are across the casting face, which is rough. Therefore, the contact between the probe and the specimens is not perfect; while in the Y direction, measurements are taken through two moulded faces.

4.6. CONCLUSIONS

- The NDT method used for this particular work is a reliable, feasible, easy, and a low costing method.
- According to the inductance results of L_x , L_y , and L_z , it is concluded that the inductance is increasing as the fibre content is increasing, in both random and oriented specimens.
- The inductance results exhibit higher values in oriented specimens along X direction; however, in random specimens all the results for a specific fibre content is almost close to each other.

- Mean relative magnetic permeability is increasing linearly in both random and oriented specimens. Moreover, neglecting the results of specimens with 4% of fibre content, both random and oriented specimens have almost similar fibre content indicator. In this case, it proves the fact that the fibre content indicator is independent of the fibre orientation.
- By comparing the fibre content indicator results of 2D and 3D measurements, it is noticed that the fibre content indicator is higher in 2D than in 3D measurements. It is expected for oriented specimens since the inductance results of X direction have higher values; however, for random specimens theoretically it is expected to have almost same fibre content indicator of 3D measurements.
- According to the achieved results, it is concluded that the third direction measurements should not be neglected.
- In order to prove the effect of 3D measurements, it is suggested to carry out an experimental campaign of large plates. Moreover, compare the 2D measurement results with the 3D measurement results done on the extracted small cubic specimens from the plates.
- As a limitation of this work, is that no information related to the size of the fibres can be achieved. Moreover, there are laboratory errors during measurements that can refer to, not having a complete contact in between specimens and probes during measurements (air gap), due to small defects on cast surface, (the cast surface is not completely parallel to moulded surface due to shrinkage).

5

TEST PROGRAMME 2: SMALL PLATES

5.1. OBJECTIVES

According to the procedure described in Chapter 4, which was discussing the third direction measurements performed on small cubic specimens, and representing the results, and limitations of the work, in this chapter it is more concentrated on 2D non-destructive measurements done on small plates. Moreover, this chapter considers more details and focuses on a specific factor of “surface effect” in NDT measurements done on a particular group of specimens.

As a result, the main purpose of this experimental campaign is to get the inductance measurements (L) done on small plates regarding to different surfaces of moulded, cast, and smoothed (smoothing the cast surfaces). In the other words, the main objective of this chapter is to evaluate, and assess reliable fibre content and orientation indicators and study the effect of different surfaces on fibre content and orientation indicators by using NDT method.

In this campaign, the tests were carried out on small plates of $200 \times 200 \times 30 \text{ mm}^3$ with different fibre dosages of 1%, 2%, 3%, and 4%. The main reason of choosing these particular dimensions for the specimens, relies on the results of the previous experiments done on the plates of $350 \times 350 \times 30 \text{ mm}^3$, studying the area effect in NDT measurements done by A. Sine, M. Pimentel, S. Nunes ([s.d.]) in 2019, (the paper is under publication). According to the previous campaign, measuring inductance on the centre point of the specimens and cutting every 25 mm from each side, it was proved the results are affected with the fibres inside the radius of 200 mm. See Figure 58 related to area effect study. The measurements in the present campaign were applied on two types of random (R), and oriented (O) specimens. Moreover, the random specimens were cast in two different directions: horizontally, and vertically; however, the oriented ones were only cast horizontally. The point of having different casting directions is to increase the opportunity of studying all types of surfaces, representative of different casting methods in strengthening of structural elements by UHPFRC, in order to reach to as precise and reliable results as possible. Additionally, all the measurements were done on the centre point of the specimens every 15° . The purpose of getting results every 15° is to increase the accuracy of the results. All details about the present work are described in the following sections.

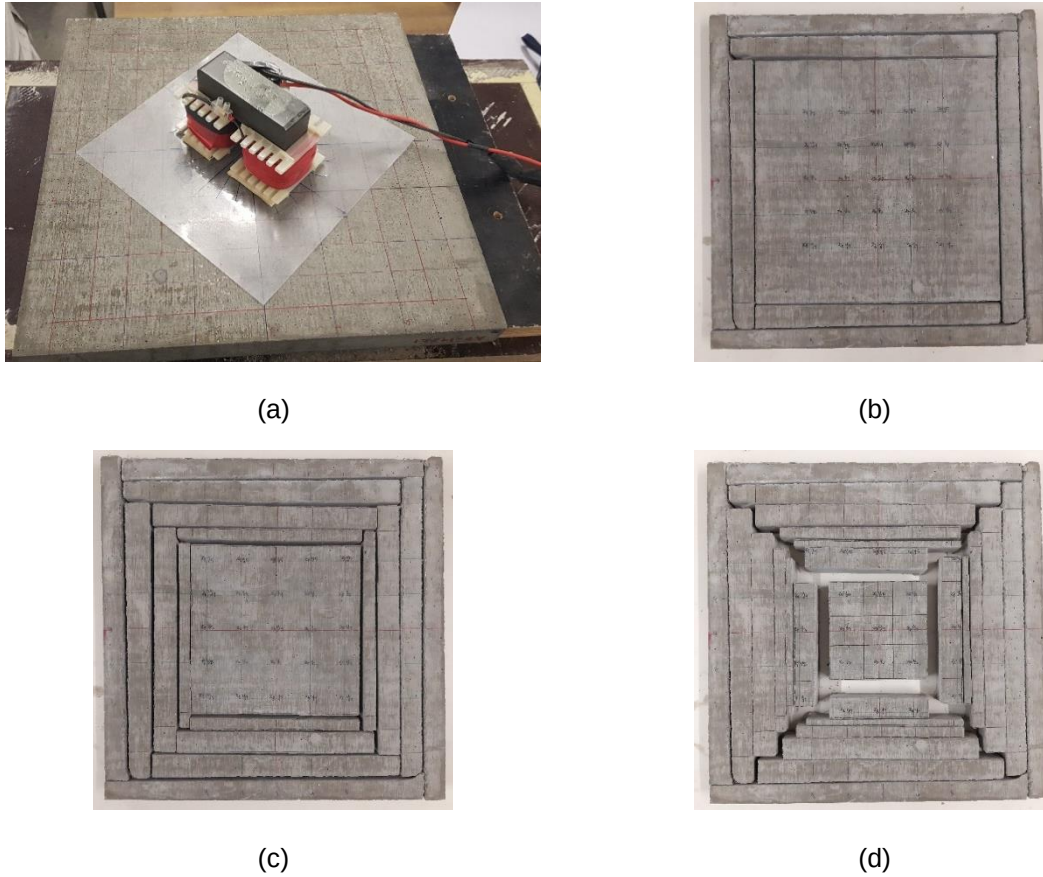


Figure 58. Area effect study in specimens of 350x350x30 mm³. Inductance measurements done on the specimen in the centre point (a), cutting specimen in the intervals of 25 mm (b), (c), (d) (Sine, Pimentel and S. Nunes, [s.d.]).

5.2. MATERIALS AND MIXTURE PROPORTIONS

Materials used for the mixtures in the present work are the same as the materials used for the small cubic specimens explained in the previous chapter with the same type of Krampharex fibres but with different lengths. The mixture consists of cement type (I) with the strength class of 42.5 R, limestone filler, silica fume, fine aggregate ($d_{\max} = 0.6\text{mm}$) and fibres. The mixture included also a polycarboxylate-based superplasticizer with the specific gravity of 1.08 and 40% solid content. For more details, see section 4.2. In this mixture, the straight micro steel fibres of Krampharex with the length of 9 mm and 12 mm and the cross section diameter of 0.175 mm were used. The fibres have the tensile strength of 2100 MPa, with the aspect ratio (l_f/d_f) of 51 and 69, respectively (Abrishambaf, Pimentel and Nunes, 2017) (Matos *et al.*, 2018).

As discussed in chapter 4, in order to have a flowable and homogenous mixture an appropriate proportion of the materials has to be mixed. The mix proportion of the present work is the same as the mix proportion used for the cubic specimens test. However, to better understand, the mix proportion is characterized in Table 11. Moreover, each mix in the table designates the total fibre dosage used in, for instance, Mix 1 refers to the mixture with 1% of total fibre content. Additionally, each mix was prepared for the volume of 1.25 litres.

Table 11. Proportion of the materials used in the mixture (kg/m³).

Constituent	Mix 1	Mix 2	Mix 3	Mix 4
Cement	794.9	794.9	794.9	794.9
Silica fume	79.49	79.49	79.49	79.49
Limestone filler	311.43	311.43	311.43	311.43
Sand	993.562	967.262	940.962	914.662
Water	145.36	145.36	145.36	145.36
Superplasticizer	30	30	30	30
Fibres of 9 mm (volume fraction)	39.25 (0.5%)	78.5 (1%)	117.5 (1.5%)	157 (2%)
Fibres of 12 mm (volume fraction)	39.25 (0.5%)	78.5 (1%)	117.5 (1.5%)	157 (2%)

5.3. MIXING, CASTING AND PREPARATION OF THE SPECIMENS

5.3.1. MIXING PROCEDURE

The mixing process is the same as the mixing process explained in detail in Table 5 section 4.3.1. At the end of the mixing, slump flow test was carried out.

5.3.2. FRESH STATE CHARACTERIZATION

At the end of mixing, the slump flow test was carried out, to check the flowability of the material. In the process of slump flow test, two opposite diameters of the spread area of the material were measured, and flow diameter was determined by the mean value of two measured diameters. More information in regarding to the process is described in 4.3.2. The spread area of the material during slump flow test is represented in Figure 59 (a) for Mix 1 and (b) for Mix 4. As it is obvious in Mix 4 due to the higher percentage of fibres, some clumps and fibre agglomeration can be observed in the final spread area (see Figure 59 (b)).



(a)



(b)

Figure 59. Spread area of the material in Mix 1 (a), and Mix 4 (b).

5.3.3. SPECIMENS PREPARATION

After slump flow test, for each Mix, three series of specimens (plates of $200 \times 200 \times 30 \text{ mm}^3$) were cast separately. Horizontal oriented, horizontal random, and vertical random. For random series either horizontally or vertically cast, the material was poured randomly in all directions inside the mould. Figure 60 represents the casting of horizontal random specimens and Figure 61 shows the casting of the vertical random specimens. Randomly casting of the specimens is recognizable in the aforementioned figures.



(a)



(b)

Figure 60. Random specimens casting horizontally (a), (b).



(a)



(b)

Figure 61. Random specimens casting vertically (a), (b).

However, for the oriented group of specimens, casting procedure was done in a pre-defined path (parallel to the magnetic field) as shown in Figure 62 (a). Moreover, for orienting and aligning the specimens along a particular direction, the casting was performed inside the orientation set-up, which is explained in detail in chapter 4, section 4.3.3. As a result, the fibres were forced to be oriented along a preferential direction, which was named as X direction. In order to guarantee the proper orientation of the fibres, the magnetic field was maintained after casting for about 6-7 hours. Figure 62 (b) designates the process of casting oriented specimens inside the fibre orientation set-up and Figure 63 shows the specimen after casting inside the fibre orientation set-up.

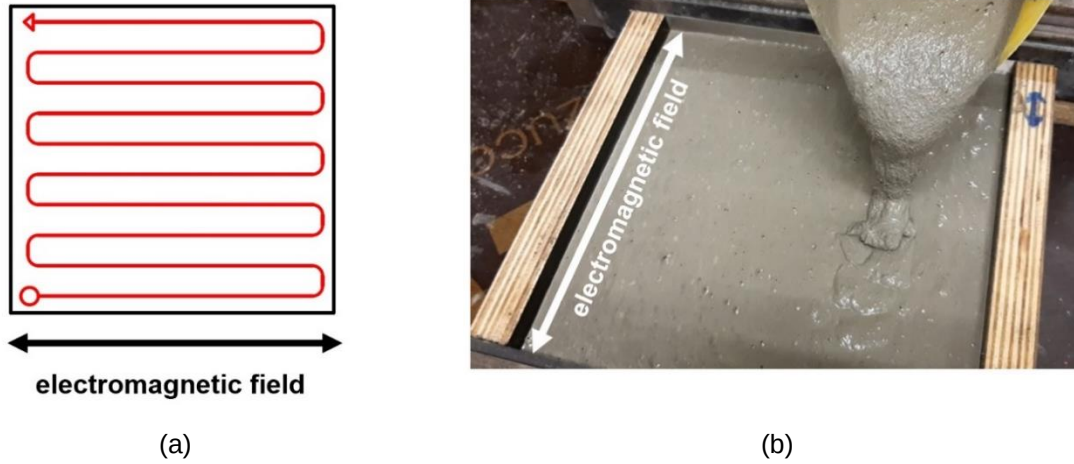


Figure 62. Casting path in oriented specimens in a well-organized way (a), oriented specimen during casting inside the fibre orientation set-up (b).

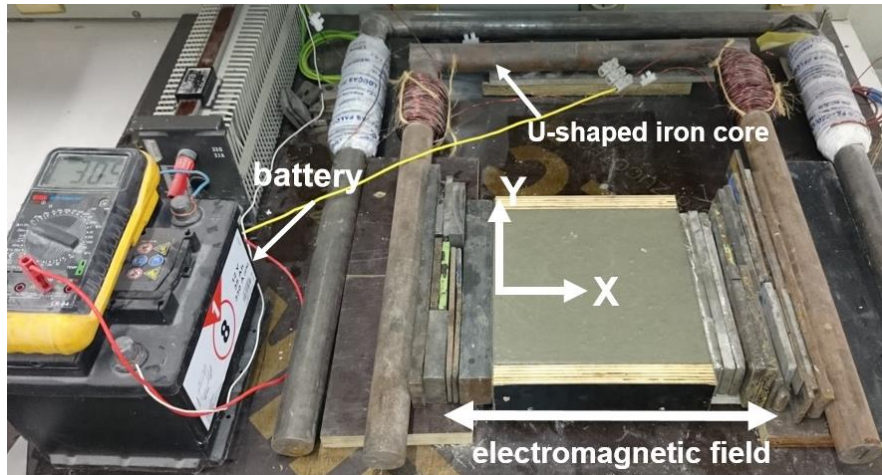


Figure 63. Oriented specimen after casting kept inside the fibre orientation set-up.

The specimens were demoulded 24 hours after casting and were kept in a chamber under controlled environmental conditions (Temp 20 °C and HR $\approx$ 95-98%) until testing. Figure 64 represents the specimens after demoulding.

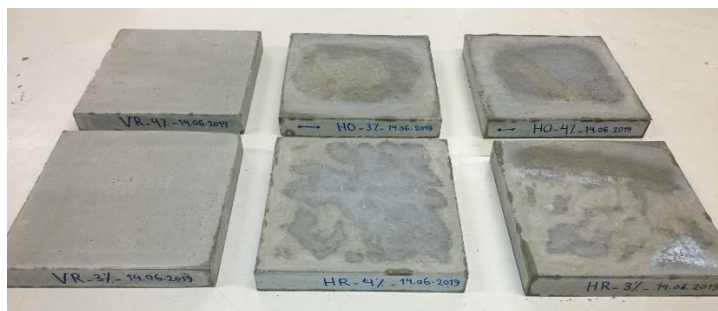


Figure 64. Specimens demoulded 24 hours after casting.

Three series of specimens for each Mix were prepared, which means 12 specimens in total (see the references in Table 12). As the same procedure used in the previous work, the specimens in this work were referenced with the letters of “R” for random and “O” for the oriented ones. Moreover, the specimens were named as “H” for horizontally cast and “V” for the vertically cast ones. In addition, the specimens were referenced according to their surfaces in the test conditions; moulded, cast, and smoothed. (See Table 12). Furthermore, after having the measurements done on the cast surfaces, the specimens were polished and smoothed by using an especial machine. (Figure 65). Afterward, the measurements were done on the smoothed cast surfaces. As an example, in the mentioned table HOM1 designates the oriented specimens cast horizontally with 1% of fibre content in which the measurements were done on the moulded surface. The process of referencing is the same for all the other specimens.

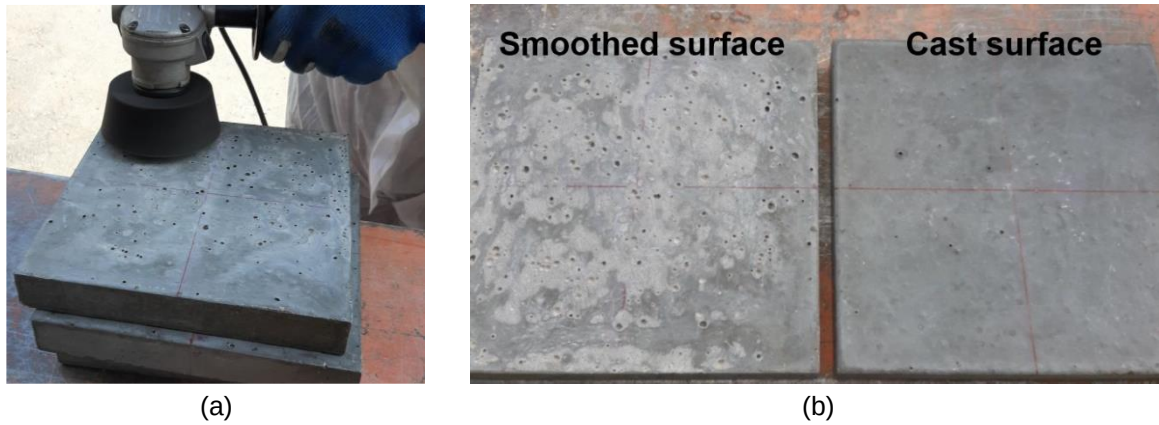


Figure 65. Process of smoothing casted surface (a), comparison of casted and smoothed surfaces (b).

Table 12. Specimens and test conditions' reference.

Casting direction	Fibre orientation	Surface reference	Name	Fibre content	Specimen reference in the test
Horizontal (H)	Oriented along X direction (O)	Moulded (M)	HOM	1%	HOM1
				2%	HOM2
				3%	HOM3
				4%	HOM4
		Casted (C)	HOC	1%	HOC1
				2%	HOC2
				3%	HOC3
				4%	HOC4
		Smoothed (S)	HOS	1%	HOS1
				2%	HOS2
				3%	HOS3
				4%	HOS4

Vertical (V)	Random (R)	Moulded (M)	HRM	1%	HRM1
				2%	HRM2
				3%	HRM3
				4%	HRM4
		Casted (C)	HRC	1%	HRC1
				2%	HRC2
				3%	HRC3
				4%	HRC4
		Smoothed (S)	HRS	1%	HRS1
				2%	HRS2
				3%	HRS3
				4%	HRS4
Vertical (V)	Random (R)	Moulded Right (MR)	VRMR	1%	VRMR1
				2%	VRMR2
				3%	VRMR3
				4%	VRMR4
		Moulded Left (ML)	VRML	1%	VRML1
				2%	VRML2
				3%	VRML3
				4%	VRML4

5.4. INDUCTANCE MEASUREMENTS

Inductance measurements were carried-out by using the high-precision Agilent E4980A LCR meter, the same as the one used in the previous campaign. The process of measuring inductance was by placing the probe on the centre point of each specimen and getting the inductance results every 15° up to 180°, regarding to the given reference in Table 12. The measurements from 180° up to 360° are the same as the results of the measurements from 0° up to 180°, since by rotating the probe each time two facing angles were measured. Figure 66 (a), (b) illustrates the process of inductance measurements.

As another significant point, which had to be taken in to account, was the direction of rotating the probe on the specimens. It has to be taken into account that in a specimen on one surface, if the rotating direction of the probe was clockwise, for the other surface it had to be counter clockwise, to achieve correct results. In order to guarantee the reliability of the results, all the measurements were taken away from any other ferromagnetic objects. In this campaign, the inductance of air was measured by keeping the probe in space, away from any other ferromagnetic objects including the specimens as well (Nunes, Pimentel and Carvalho, 2016).

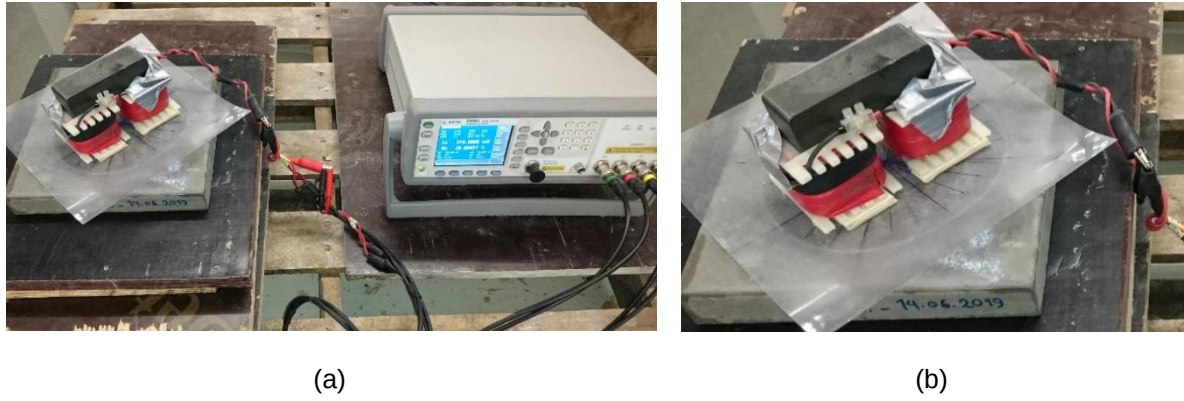


Figure 66. Inductance measurements on plates.

5.5. RESULTS AND ANALYSIS

5.5.1. FRESH STATE RESULTS

Fresh state results related to the slump flow test done in section 5.3.2, are presented in Table 13 for all the mixes. It is concluded that, all the mixtures show a very close average flow diameter, which is the proof of good flowability of the material.

Table 13. Slump-flow test results.

Mixture Specimen reference	Date of casting	D1 (mm)	D2 (mm)	Average diameter (mm)
Mix 1				
HR1	12/06/2019	291	300	295.5
HO1		282	290	286
VR1		283	294	288.5
Mix 2				
HR2	12/06/2019	286	292	289
HO2		281	294	287.5
VR2		284	289	287
Mix 3				
HR3	14/06/2019	285	290	287.5
HO3		279	289	284
VR3		283	292	288
Mix 4				
HR4	14/06/2019	271	291	281
HO4		268	293	280.5
VR4		269	278	274

5.5.2. INDUCTANCE RESULTS IN THE CENTRE POINT OF EACH SPECIMEN (L) :

Inductance results from the measurements due to the process explained in Section 4.4 are summarized in detail in Table A 1 and Table A 2 for horizontal oriented, in Table A 3 and Table A 4 for horizontal random and in Table A 5 and Table A 6 for vertical random specimens in Appendix. The tables reveal inductance measurements in the centre point of each specimen every 15°.

In order to better clarify the results, Figure 67 indicates the relative magnetic permeability ($\mu_{r,\theta i} \cong \frac{L_{\theta i}}{L_{air}}$) (explained in detail in Section 4.5.3) in all specimens according to the inductance results as a function of angle.

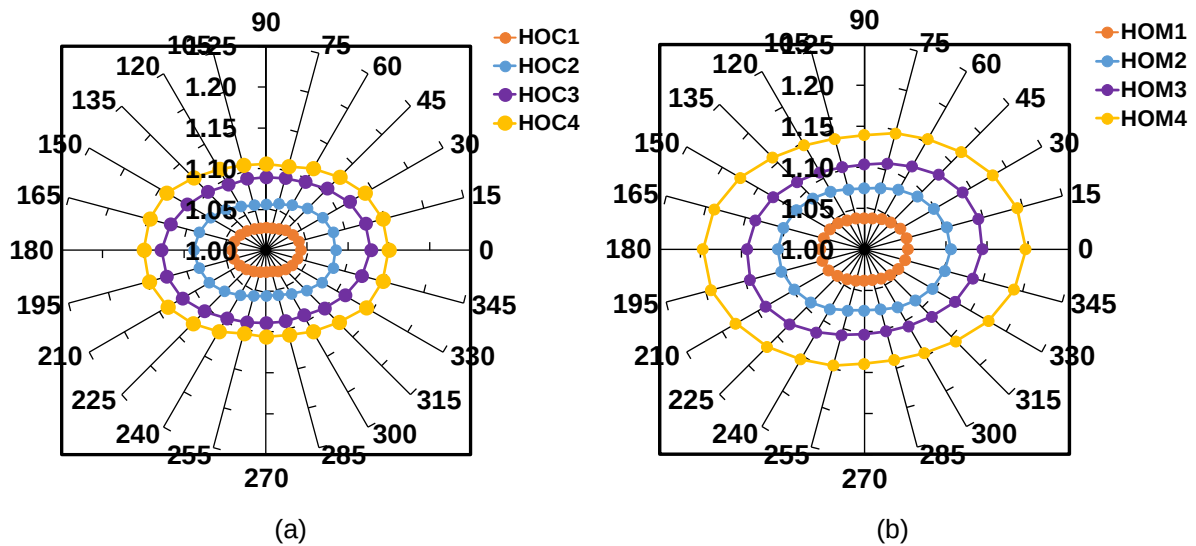
According to Figure 67, in the first place, it is concluded that by increasing the fibre content, relative magnetic permeability and consequently the inductance is increasing in all specimens. As it is observed in horizontally casted specimens (both random and oriented), the relative magnetic permeability in all the surfaces are not the same. It can be explained in a way that, inductance results in horizontally cast specimens (both random and oriented) in moulded surfaces are higher than the results in cast surfaces.

This can be expected since the cast surfaces (irregular surfaces) generate air gaps in between the specimens and probe during the measurements. On the other hand, by smoothing the surfaces to achieve a more regular surface for measurements, an increase in the inductance results can be observed.

However, the obtained results from the smoothed surfaces are still lower than the results of the moulded surfaces. This can be clarified in a way that, the steel fibres tend to segregate towards the bottom surface (moulded surface) which lead to a slightly increase in the inductance measurements and consequently relative magnetic permeability results.

However, in vertically cast specimens the relative magnetic permeability results in both moulded surfaces are very close to each other and almost same. It is logical since both moulded surfaces did not have recognizable roughness and irregularity.

Another significant point is the difference between the inductance results of 0° and 90° in the oriented specimens. It was expected since the specimens were oriented along X direction or 0° , therefore the results along 0° would be higher than the results along 90° direction. Therefore, the relative magnetic permeability measured in different directions clearly represents an ellipse shape.



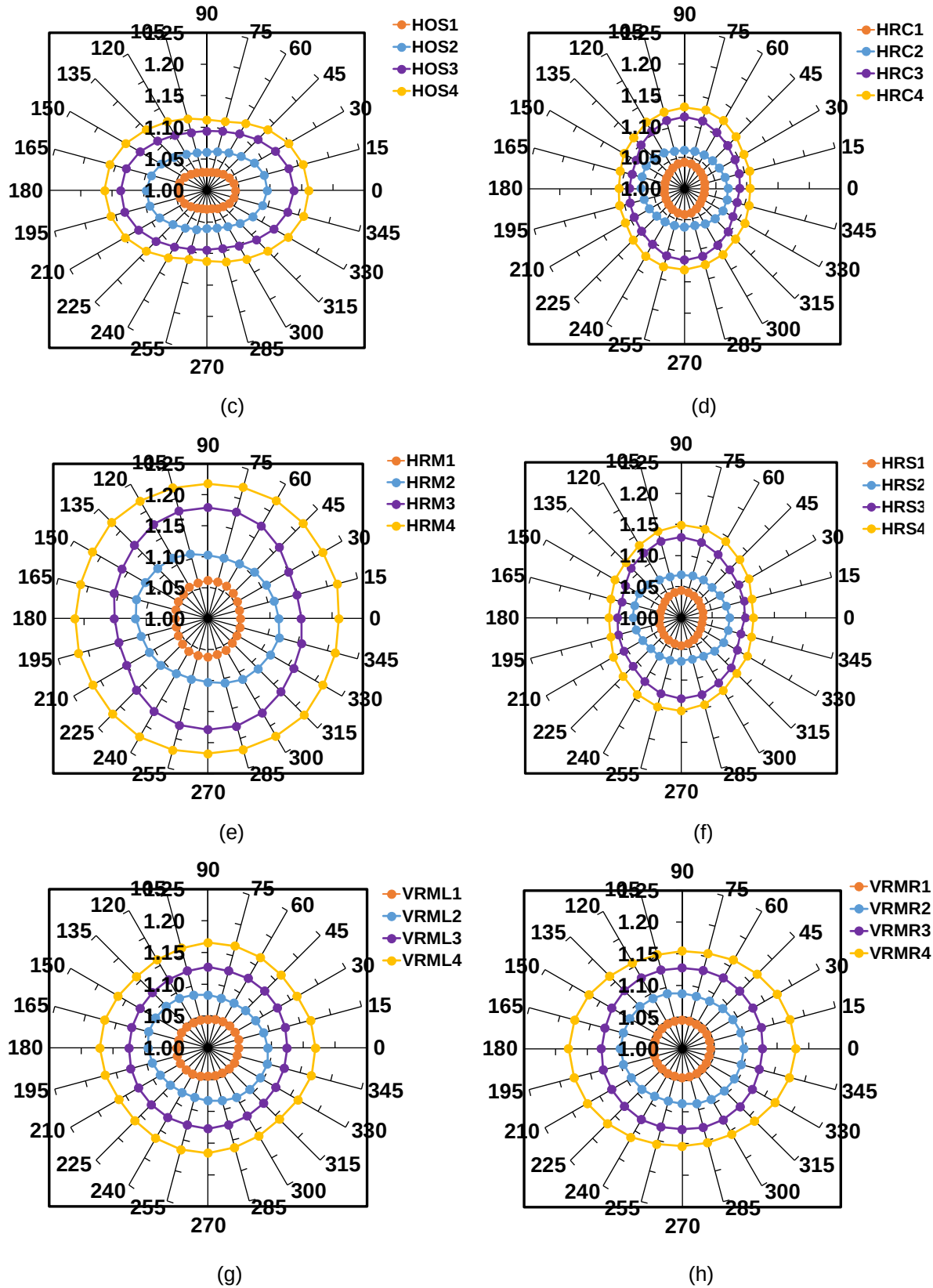


Figure 67. Relative magnetic permeability in horizontal oriented specimens casting surface (a), moulded surface (b), and smoothen surface (c). In horizontal random specimens (d), (e), and (f), and vertical random specimens (g), and (h).

According to Figure 67, the graphs guarantee the accuracy of both casting and measurements. In horizontal random specimens, some fibres orientation can be observed especially on the casting surface. Although the specimens were cast randomly, the flow of the mortar forced some preferential orientation of the fibres in specimens.

In order to better clarify and compare the inductance variations in different surfaces, a comparison of relative magnetic permeability measurement for different surfaces for each fibre dosages is shown in Figure 68 for horizontal random specimens and in Figure 69 for horizontal oriented specimens and in Figure 70 for vertical random specimens.

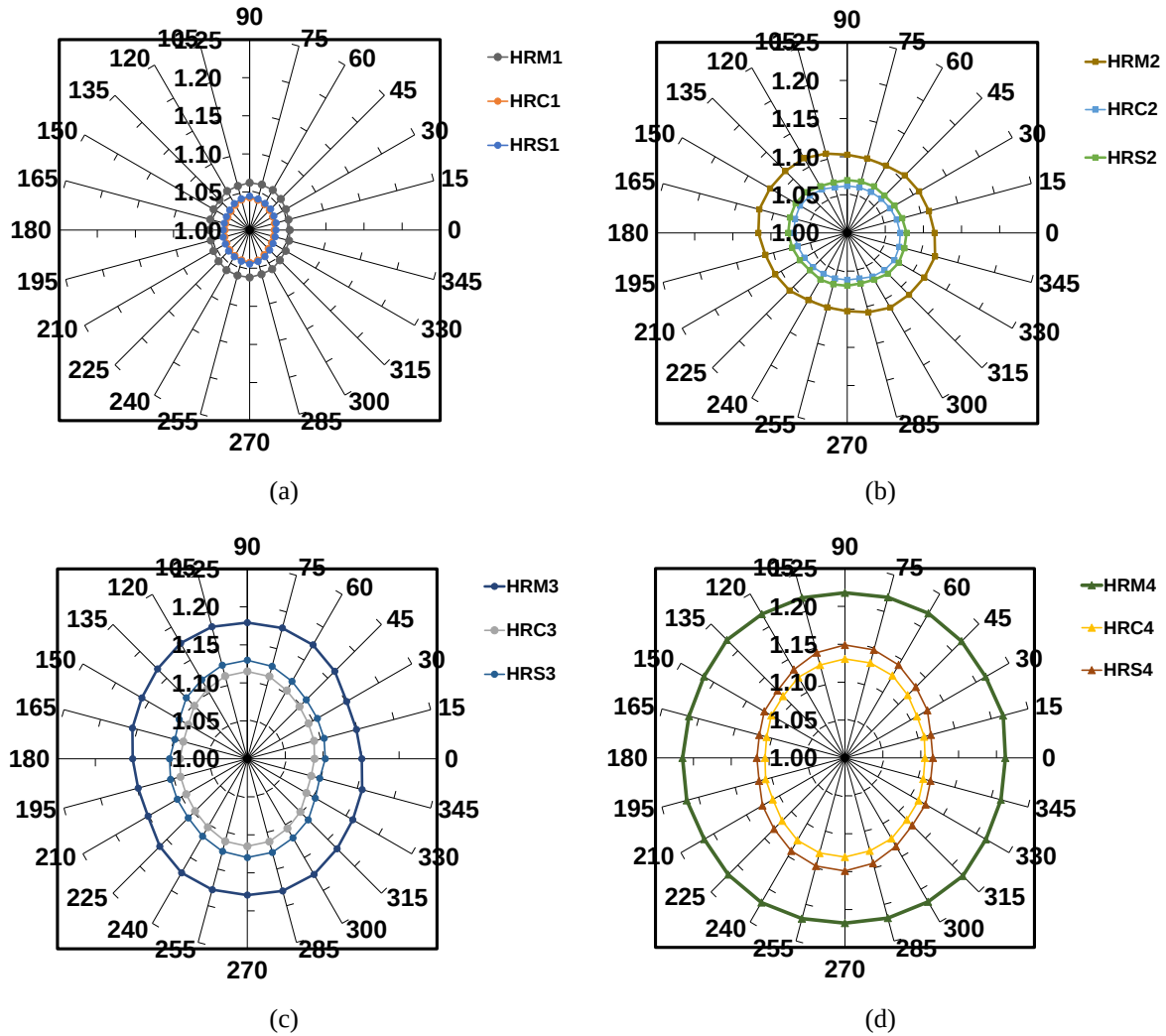


Figure 68. Relative magnetic permeability results in horizontal random specimens comparing the surfaces for each fibre content. Specimens with 1% fibre content (a), 2% fibre content (b), 3% fibre content (c), and 4% fibre content (d).

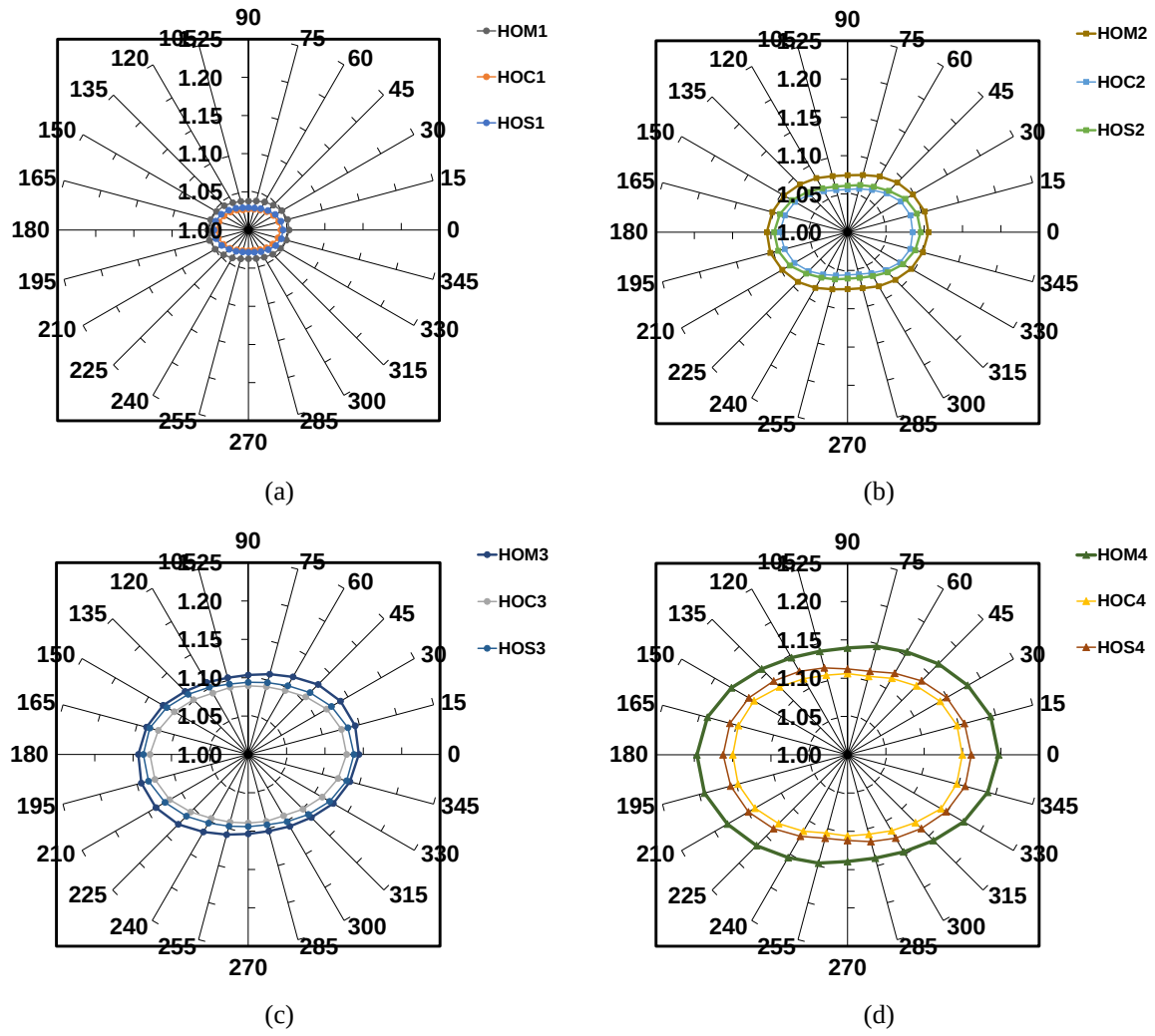
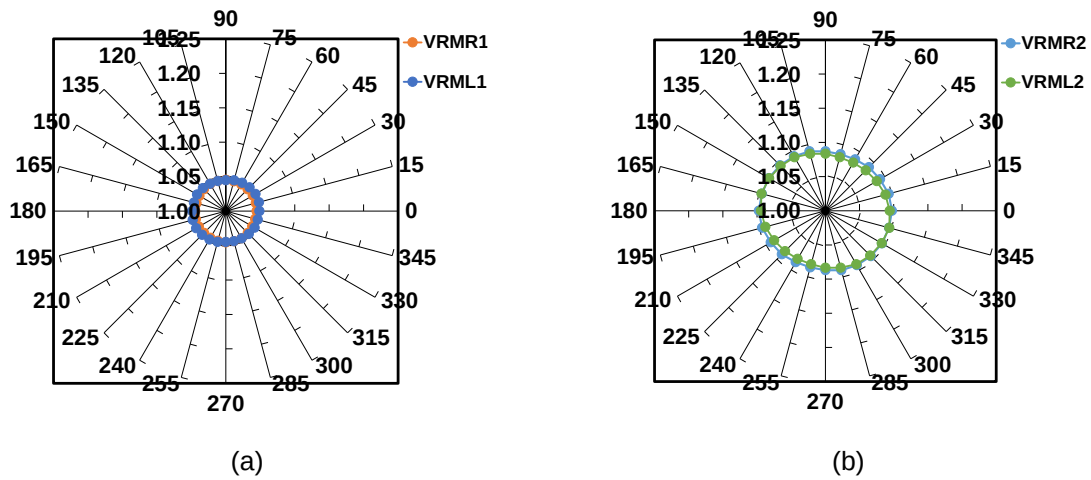


Figure 69. Relative magnetic permeability results in horizontal oriented specimens comparing the surfaces for each fibre content. Specimens with 1% fibre content (a), 2% fibre content (b), 3% fibre content (c), and 4% fibre content (d)



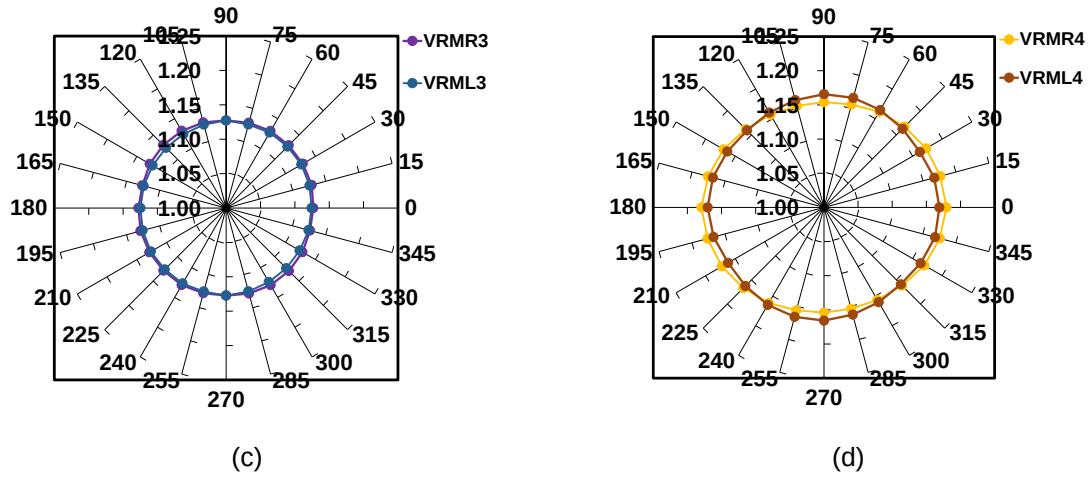


Figure 70. Relative magnetic permeability results in vertical random specimens comparing the surfaces for each fibre content. Specimens with 1% fibre content (a), 2% fibre content (b), 3% fibre content (c), and 4% fibre content (d).

By comparing Figure 68 and Figure 69, it can be observed that the difference in between the results of μ_r in different surfaces for random specimens is higher than the results for the oriented specimens. One hypothesis can be in a way that, in oriented specimens the external force (magnetic field) prevents the fibres form segregation. However, this hypothesis needs to be proven by image analysis.

5.5.3. FIBRE CONTENT INDICATOR

The relative magnetic permeability as a function of angle is represented in Figure 71 for horizontal oriented specimens in cast surface (a), smoothed surface (b), and moulded surface (c).

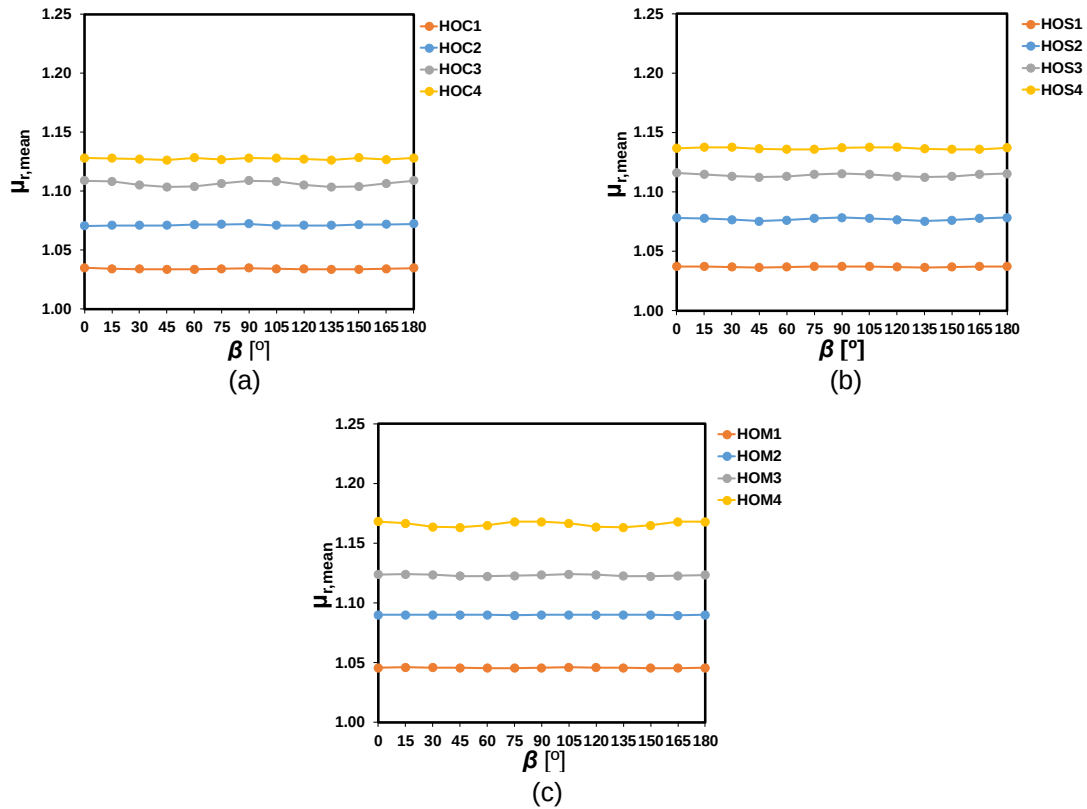


Figure 71. Mean relative magnetic permeability in horizontal oriented specimens casting surface (a), smoothed surface (b), and moulded surface (c).

As it is shown in Figure 71, $\mu_{r,mean}$ in cast and smoothed surfaces for fibre contents of 1%, 2%, and 3% is increasing linearly; however, it does not follow the same rule in specimens with 4% of fibre content. Furthermore, the values of $\mu_{r,mean}$ in moulded surfaces is higher than in the smoothed and cast surfaces. As discussed before, by reducing the roughness of the cast surface (smoothing surface), $\mu_{r,mean}$ increased but still is lower than the moulded surface, which is an indication of the occurrence of fibres segregation.

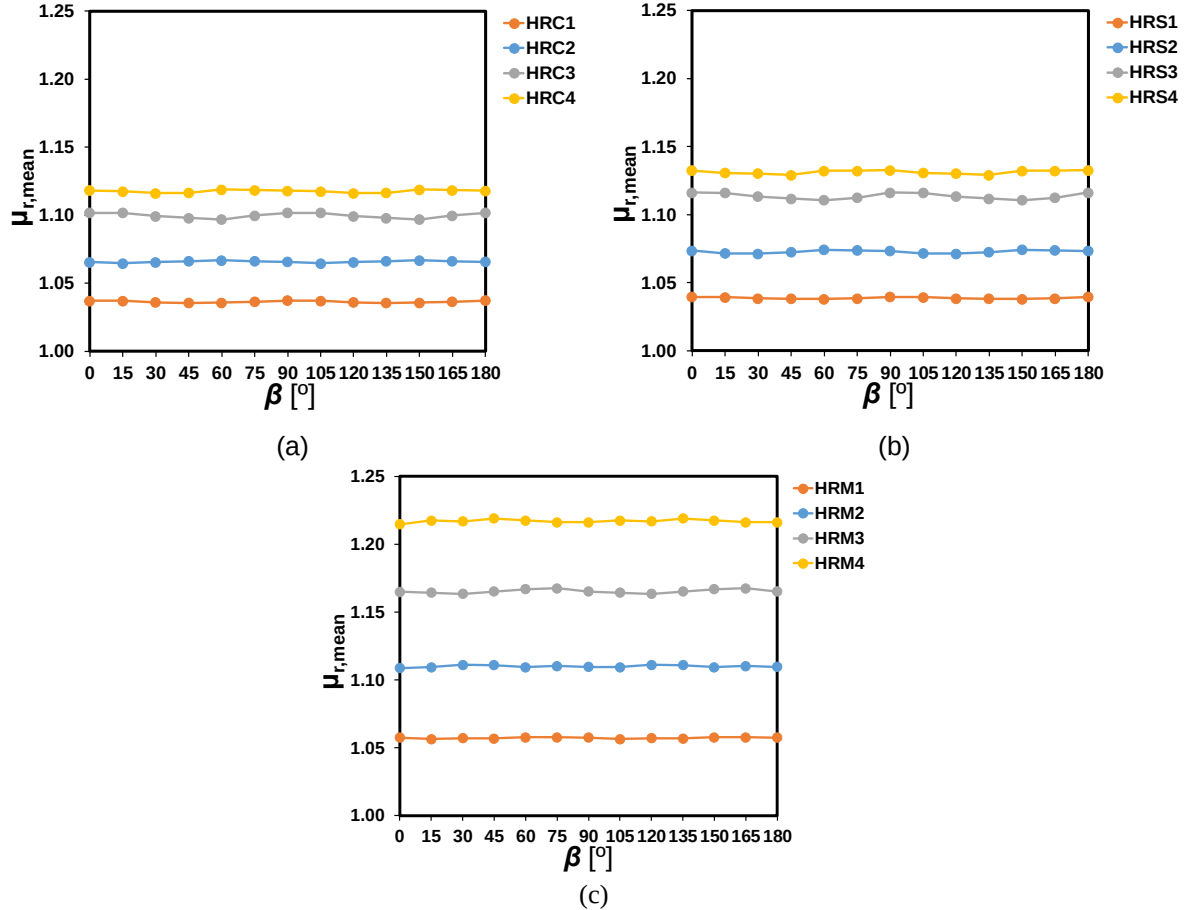


Figure 72. Mean relative magnetic permeability in horizontal random specimens casting surface (a), smoothed surface (b), and moulded surface (c).

Figure 72 presents the $\mu_{r,mean}$ in horizontal random specimens in all surfaces. The same results as oriented specimens can be observed in random specimens. Additionally, higher values of $\mu_{r,mean}$ in moulded surfaces of horizontal random specimens, is observed in comparison to the moulded surfaces of the horizontal oriented specimens.

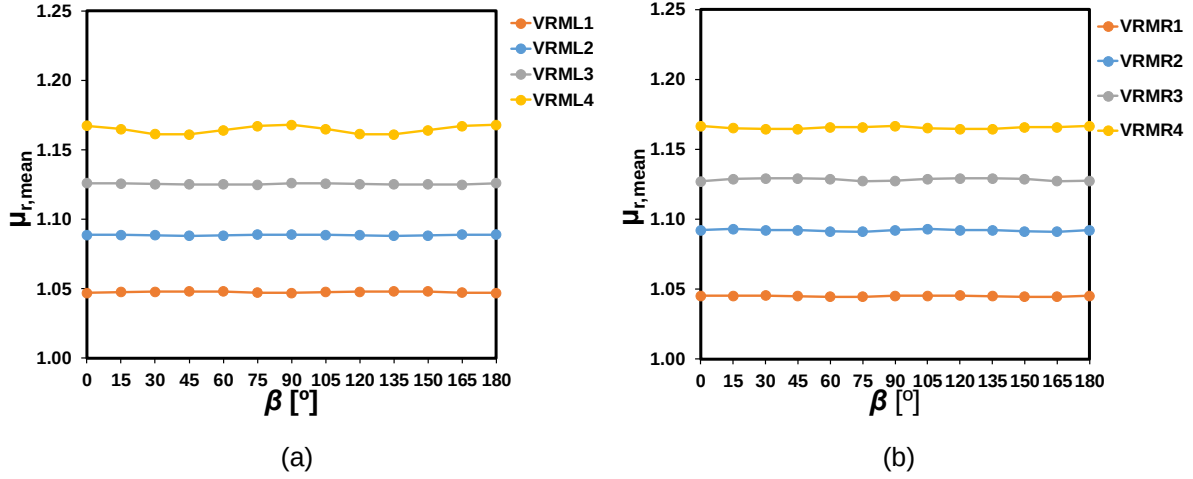


Figure 73. Mean relative magnetic permeability in vertical random specimens left-moulded surface (a), right-moulded surface (b).

Figure 73 illustrates the mean relative magnetic permeability in vertical random specimens left-moulded surface (a), and right-moulded surface (b). According to Figure 73 $\mu_{r,mean}$ is increasing almost linearly in both surfaces by increasing the fibre content. Moreover, the values of mean relative magnetic permeability in both surfaces, is almost same and very close to each other.

Based on the evaluated results, mean relative magnetic permeability as a function of fibre content (named as fibre content indicator) is presented in Figure 74 for horizontal oriented specimens.

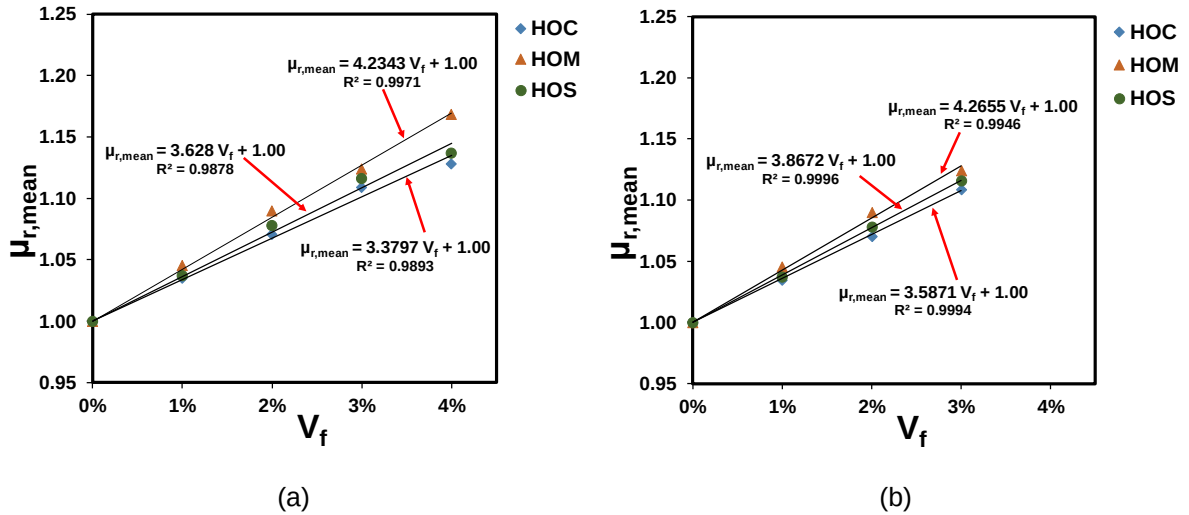


Figure 74. Fibre content indicator factor in horizontal oriented specimens including all fibre contents (a), excluding specimens of 4% fibre content (b).

According to Figure 74 a linear relation can be observed in between mean relative magnetic permeability and fibre content. Moreover, significant differences can be observed in the correlation lines especially in the specimens with 4% of fibre content. By eliminating the specimens with the fibre content of 4%, still the difference in the correlation lines of each surface can be seen. It can be concluded

that these variations are not due to the higher dosages of fibres (4% fibre content). As a result, alternative factors can cause this phenomenon such as fibre segregation.

Additionally, mean relative magnetic permeability results in horizontal random specimens are illustrated in Figure 75. As can be seen there is a significant difference in the correlation lines, particularly for the moulded surfaces. In this case, it is clearly proved that this incident is not related to the fibre content.

Figure 76, compares the fibre content indicator in random and oriented specimens both cast horizontally. According to Figure 76, $\mu_{r,mean}$ in smoothed surfaces is almost same in both specimens. However, in moulded surfaces, $\mu_{r,mean}$ in random specimens is higher than in oriented specimens. This result may show that when the specimens are cast randomly the fibres tend to segregate more than when they are subjected to an electromagnetic field during casting. However, to clearly prove it, more experimental data is needed. In casting surfaces, $\mu_{r,mean}$ in oriented specimens is slightly higher than random specimens. In this case, only for the smoothed and casted surfaces fibre content indicator is independent from the orientation of the fibres.

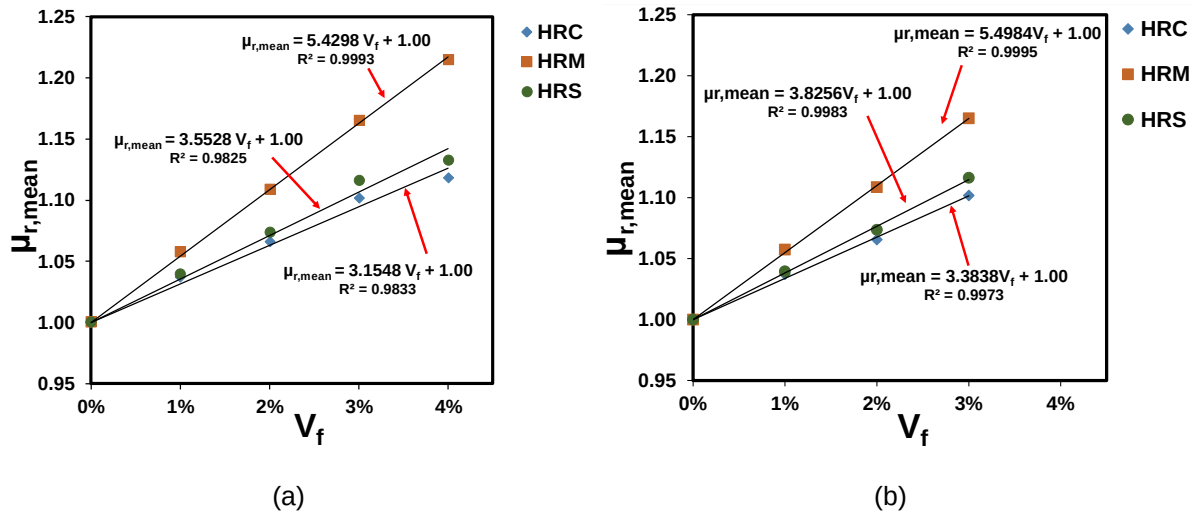


Figure 75. Fibre content indicator in horizontal random specimens including all fibre contents (a), excluding specimens of 4% fibre content (b).

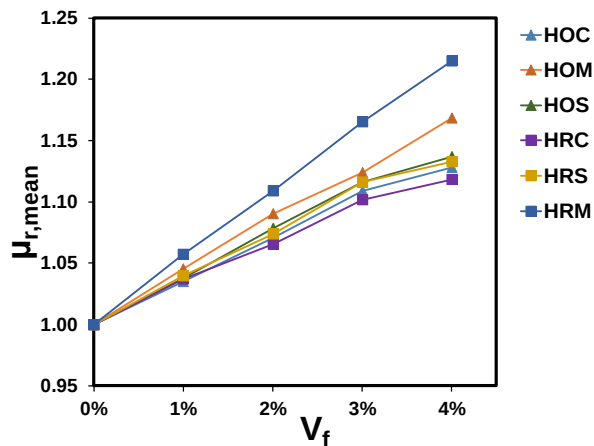


Figure 76. Comparison of fibre content indicator in random and oriented specimens casted horizontally.

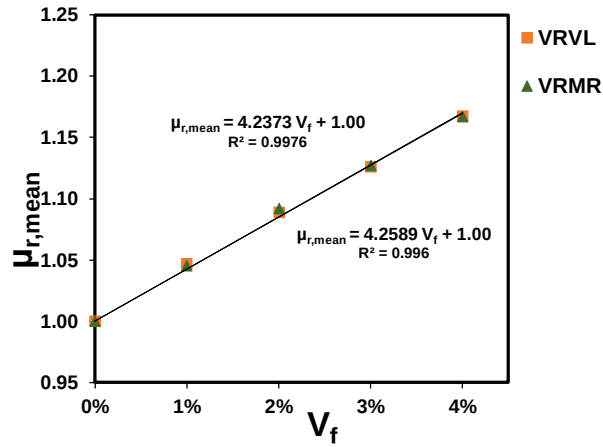


Figure 77. Fibre content indicator in vertical random specimens (a), and (b).

Figure 77 describes the fibre content indicator in vertical random specimens. According to Figure 77 in random specimens cast vertically, fibre content indicator for both moulded surfaces is almost same and very close to each other. Moreover, Figure 78 compares the fibre content indicator in random specimens regarding to the casting directions (cast horizontally and vertically). As shown in this figure, fibre content indicator can be dependent on the direction of casting (vertically or horizontally) or in this case, it can be a matter of sedimentation.

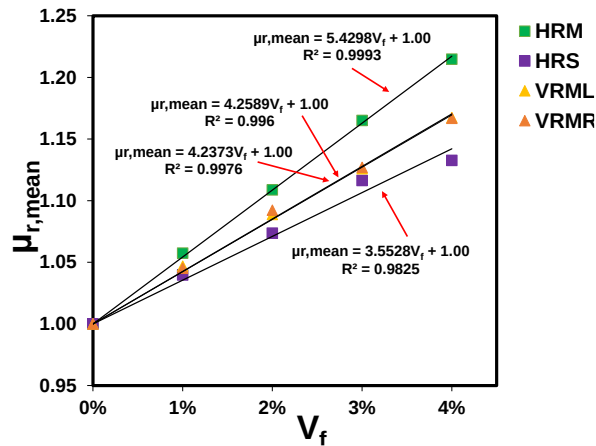


Figure 78. Comparison of fibre content indicator in random specimens casted horizontally and vertically.

5.5.4. FIBRE ORIENTATION INDICATOR

Fibre orientation factor “ $(\rho_{(90^\circ-\theta_i)} - \rho_{\theta_i})$ (%)” is calculated according to Eq. (25) discussed in detail in chapter 3 section 3.4.

The results of the fibre orientation factor are presented in Figure 79 for all the specimens in all surfaces.

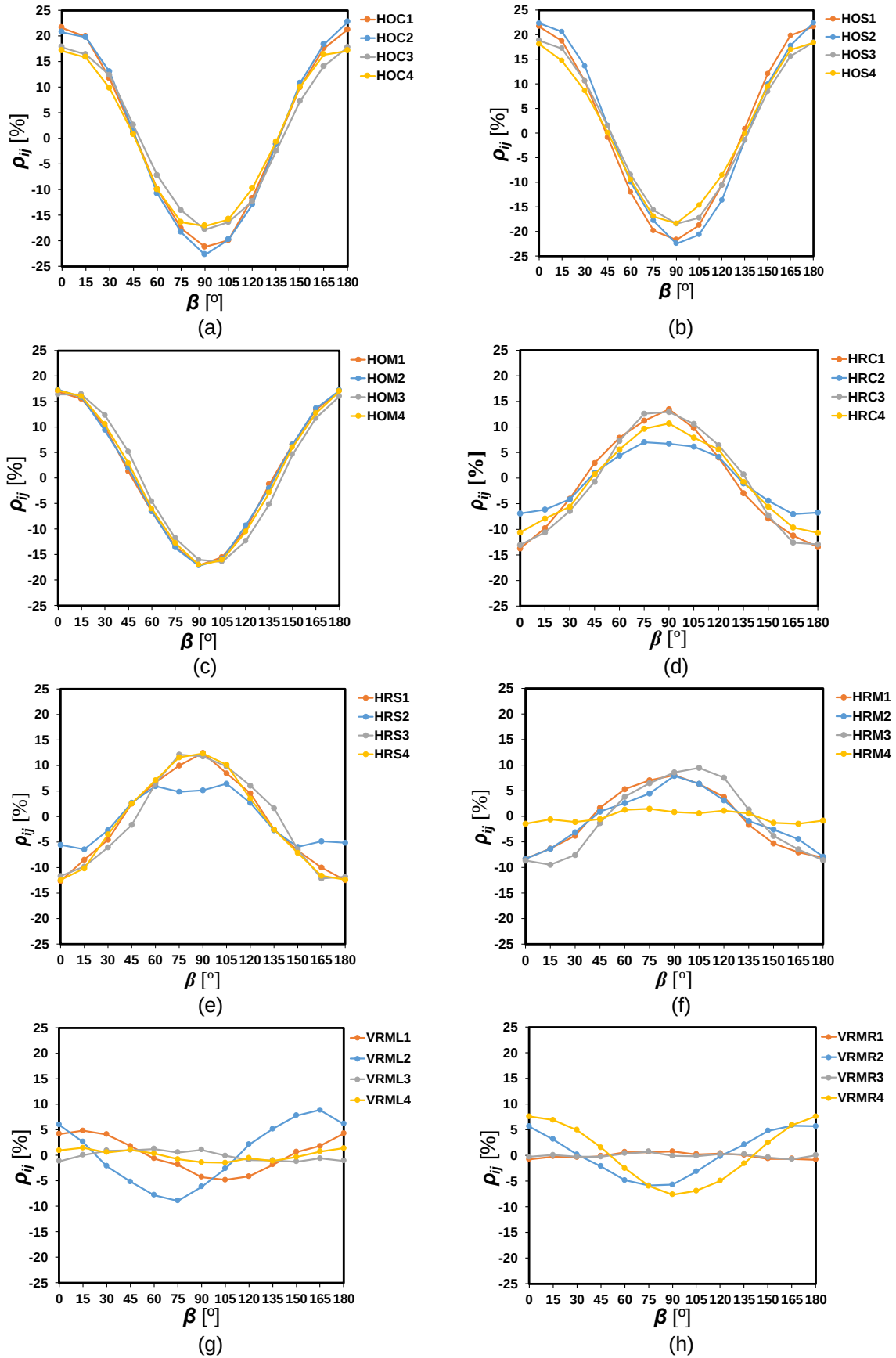


Figure 79. Fibre orientation indicator in oriented specimens (a), (b), and (c), in horizontal random specimens (d), (e), and (f), in vertical random specimens (g), and (h).

As it is presented in Figure 79, in oriented specimens for θ_i equals to 0° , the fibre orientation factor illustrates a positive value which is expected as our specimens are oriented along 0° . However, in random specimens (cast horizontally or vertically in a random way), some slight orientations can be observed which can be a result of the mortar flow.

5.6. CONCLUSIONS

- Relative magnetic permeability in horizontally cast specimens (both random and oriented) has higher values in moulded surfaces than in the cast surfaces. Possible explanations for these observations can be the irregularity (air gap) on the cast surfaces and fibres segregation.
- By smoothing the cast surfaces (eliminating air gap), still the moulded surfaces have higher values than the smoothed surfaces. In this case, the sedimentation of the fibres has to be assessed.
- In random specimens, relative magnetic permeability in moulded surfaces cast horizontally has higher values than the specimens cast vertically. This phenomenon can be due to the sedimentation of the fibres, which is favoured in horizontally casting.
- In specimens cast horizontally, moulded surfaces have higher values in random specimens than the moulded surfaces in the oriented specimens. A possible explanation is the existence of the magnetic field during casting, which prevents the sedimentation of the fibres.
- In oriented specimens, the accuracy of the results can be proved due to the ellipse shaped results, which exhibit the alignment of the fibres along 0° or X-axis.
- In random specimens cast vertically, both surfaces have almost same magnetic permeability results, which proves that the casting direction has noticeable impacts on the results rather than the absence of air gap.
- The formulated hypothesis concerning the occurrence of fibres segregation still needs to be confirmed, for example using the image analysis technique on internal surfaces cut from the specimens.

6

TEST PROGRAMME 3: CYLINDRICAL SPECIMENS

6.1. OBJECTIVES

The current chapter focuses on the effect of different thicknesses in UHPFRC elements on NDT measurements.

Therefore, the main purpose of this experimental program is to get the inductance measurements (L), on cylindrical specimens having different thicknesses in order to discover the maximum thickness up to which, the inductance measurements remain unchanged. In other words, the objective of this work is to clarify the maximum thickness in the specimens that is involved in the inductance measurements. Moreover, according to the proposed procedure, fibre content and fibre orientation indicator factors will be presented.

As a result, the tests in this campaign were carried out on cylindrical specimens with the diameter of 150 mm and a height of 100 mm with different fibre dosages of 1%, 2%, 3%, and 4%, which were cast randomly. Additionally, all the measurements were taken on the centre point of the specimens every 15° in different heights. The point of measuring inductance every 15°, as it was shown in the previous chapter, is to increase the accuracy of the results. All details about the present work are described in the following sections.

6.2. MATERIALS AND MIXTURE PROPORTIONS

The same mixtures as previously used, is also implemented in the preparation of the cylindrical specimens with the following constituents: cement type (I) with the strength class of 42.5R, limestone filler, silica fume, superplasticizer, fine aggregate and straight micro steel fibres. For more details see section 4.2. In this mixture, two types of Krampharex fibres both with the same circular cross sections with $d_f = 0.175\text{mm}$ and different lengths of 9 and 12 mm were used. The fibres have the tensile strength of 2100 MPa, with the aspect ratio (l_f/d_f) of 51 and 69 respectively (Abrishambaf, Pimentel and Nunes, 2017).

The mixture proportions with different fibre volume fractions (V_f) of 1%, 2%, 3%, and 4% are the same as the mix proportion in the previous experimental campaign. See Table 11 of chapter 5 section 5.2.

6.3. MIXING, CASTING AND PREPARATION OF THE SPECIMENS

6.3.1. MIXING PROCEDURE

The mixes were prepared in the laboratory in small batches of 1.90 litres. Mixing process is described in detail in Table 5 section 4.3.1. After the end of mixing, slump flow test was carried out to determine the flowability of the material.

6.3.2. FRESH STATE CHARACTERIZATION

The slump flow test was carried out to check the flowability of the material. The procedure is described in detail in section 4.3.2. The spread area of the material during slump flow test is represented in Figure 80 in which two perpendicular diameters of D_1 and D_2 were measured and the average of two diameters was considered as the result of the slump flow test.

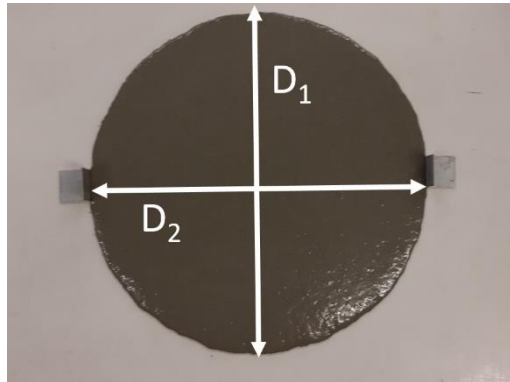


Figure 80. Spread area of the material representing two perpendicular diameters.

6.3.3. SPECIMENS PREPARATION

The specimens of each mix were cast separately after the slump flow test done. All the specimens were cast randomly just by pouring the material inside the cylindrical moulds with the height of 100 mm and cross section diameter of $\phi 150$ mm.

The specimens were demoulded 24 hours after casting and were kept in a chamber under controlled environmental conditions (Temp 20 °C and HR $\approx$ 95-98%) until testing. Figure 81 represents the specimens after being demoulded.



Figure 81. Specimens demoulded 24 hours after casting.

As can be observed from Figure 81, the plastic sheets, which were placed in the bottom of the cylinder moulds before casting, introduced some irregularities on the surfaces of the specimens. Therefore, it was necessary to smooth the surfaces of the specimens before starting doing the measurements.

The present experimental campaign consists of 4 specimens in total. The specimens were referenced precisely as shown in Table 14. In this reference, the letter “C” was chosen as a symbol for the cylindrical specimens. For instance, C1% refers to the cylindrical specimens with 1% of fibre content. Figure 82 illustrates the specimens after being referenced. As it is shown in Figure 82, the moulded surfaces of the specimens (the surface on which the measurements were done) were smoothed in order to remove the roughness of the surfaces. As discussed in the previous chapter, the smoothed surfaces lead to higher and more accurate inductance measurements. Owing to the fact that irregular surfaces creates air gaps between the probe and the specimen’s surface, which detrimentally influence the accuracy of the results. Moreover, in order to measure the height of the specimens precisely, the height of each specimen was measured every 90° according to the pattern shown in Figure 83. Furthermore, Figure 84 shows the process of measuring height in specimens.



Figure 82. Cylindrical specimens after referencing.

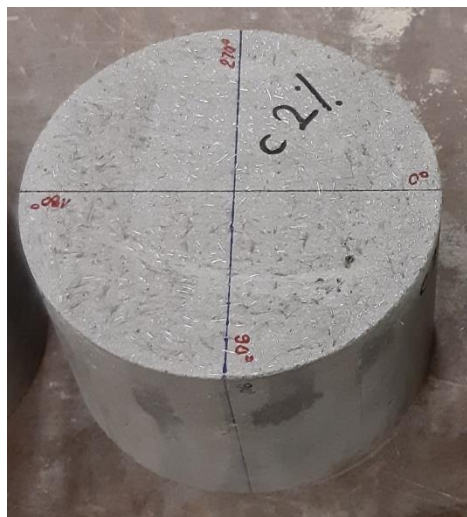


Figure 83. Reference for height measurements on the moulded surfaces.

Table 14. General reference of the cylindrical specimens.

Fibre orientation	Fibre content	Specimen reference
Random (R)	1%	C1%
	2%	C2%
	3%	C3%
	4%	C4%



Figure 84. Process of measuring height in specimens.

Additionally, after each measurement the specimens were prepared for the next measurement by cutting 10mm of their heights. Figure 85 illustrates the schematic representation of the cylindrical specimens showing the spaces between each cut. Thus, the inductance measurements were taken on different heights starting from the height of 100mm and reducing every 10mm. The reduction process was done by cutting the specimens according to the aforementioned procedure. Additionally, in order to get more precise results, after reaching to the height of 50mm the specimens were cut every 5mm instead of 10mm. Small variations of 1 or 2 mm during the cuts was acceptable.

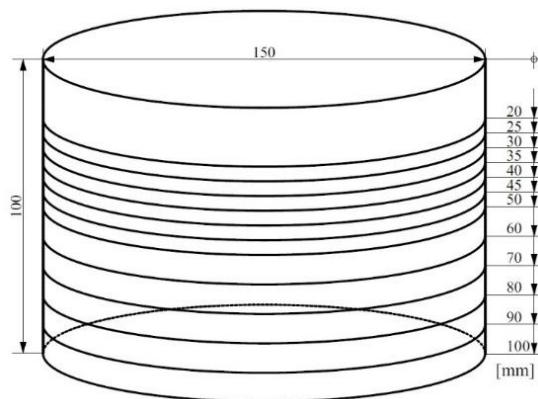


Figure 85. Schematic representation of the cylindrical specimen showing the spaces between each cut.

During the cutting process, the auxiliary specimen was glued to the main specimen in order to make the cutting procedure easier and safer. Figure 86 (a) shows the main and the auxiliary specimens, which are glued, and Figure 86 (b) represents the process of cutting the height of the specimens. Moreover, Figure 87 presents the specimens after cutting. This process was repeated for all the specimens each time for cutting 10 mm of their height. It is worth to mention that the process of gluing and cutting the specimens was a time demanding procedure and taking at least 24 hours.

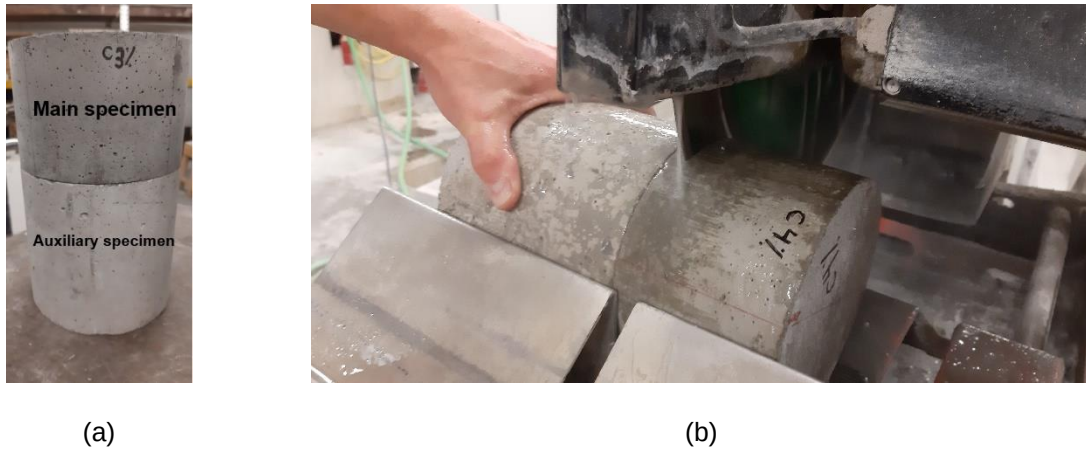


Figure 86. Main specimen being glued to an auxiliary cylindrical specimen (a), removing a thin layer (~10mm) from the cylindrical specimen (b).

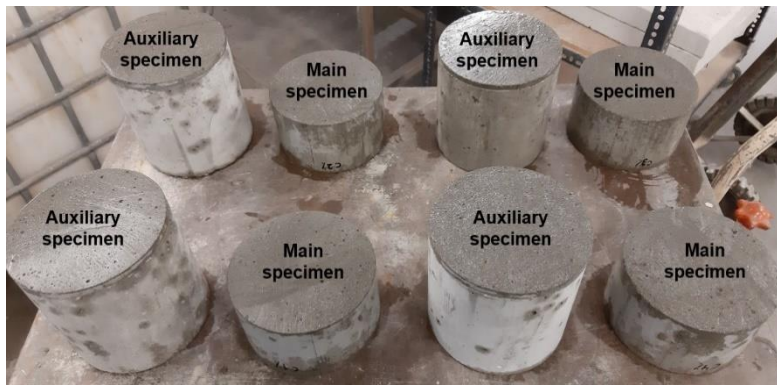


Figure 87. Specimens after cutting.

6.4. INDUCTANCE MEASUREMENTS

Inductance measurements were done by using the high-precision Agilent E4980A LCR meter the same as the one used in the previous campaigns. The process of measuring inductance was by placing the probe on the centre point of the moulded surfaces of the specimens and getting the inductance results every 15° up to 180°.

As another significant point, which had to be taken into account, was the direction of measuring inductance on specimens. The measurements started at 0° (see Figure 83) and were taken every 15° by rotating the probe clockwise. Moreover, all the measurements were done on the moulded surfaces and

all the cuts were applied on the cast surfaces. To guarantee the reliability of the results, all the measurements were taken away from any other ferromagnetic objects. Also, the inductance of the air was measured by keeping the probe in space, away from any other ferromagnetic objects including the specimens as well (Nunes, Pimentel and Carvalho, 2016).

6.5. RESULTS AND ANALYSIS

6.5.1. FRESH STATE RESULTS

Fresh state results related to the slump flow test done in section 4.3.2, are illustrated in Table 15. It is concluded that, all the mixtures show a very close average flow diameter, which is the proof of the good flowability of the material. However, in Mix 4 a slight variation can be observed which is related to the high percentage of the fibres used in this mixture.

Table 15. Slump-flow test results

Mixture	Mix 1	Mix 2	Mix 3	Mix 4
Date of casting	22/05/2019	22/05/2019	22/05/2019	22/05/2019
D1 (mm)	297	297	291	255
D2 (mm)	292	293	292	271
Average diameter(mm)	294.5	295	291.5	263

6.5.2. INDUCTANCE RESULTS IN THE CENTRE POINT OF EACH SPECIMEN (L) :

Inductance results from the measurements according to the process explained in section 6.4 are summarized in detail in Tables A7-A10 in appendix. All the results in the tables consider the measurements in the centre point of each specimen every 15°.

As it was already shown in previous chapters, by increasing the fibre content the inductance results are also increasing in all specimens. As an interesting phenomenon, comparing the inductance results in the largest heights with the lowest heights in all specimens, it can be observed that by reducing the height the inductance results are decreasing as well. However, the reduction in inductance is lower in the beginning and increases while the thickness is reducing.

To better understand the results, the relative magnetic permeability ($\mu_{r,\theta i} \cong \frac{L_{\theta i}}{L_{air}}$) (explained in detail in section 3.3) is indicated in Figure 88 for all the specimens according to the laboratory inductance results as a function of angle. Furthermore, the inductance results in each slice in all measuring directions of θ is almost same which was expected since all the specimens were cast randomly without any preferential orientation of the fibres. Nevertheless, in Mix 4, some slight variation can be observed in some directions of θ . In this case, some orientations might have occurred by the flow of the material during casting. The results shown in the graphs guarantee the accuracy of the castings, which were done randomly.

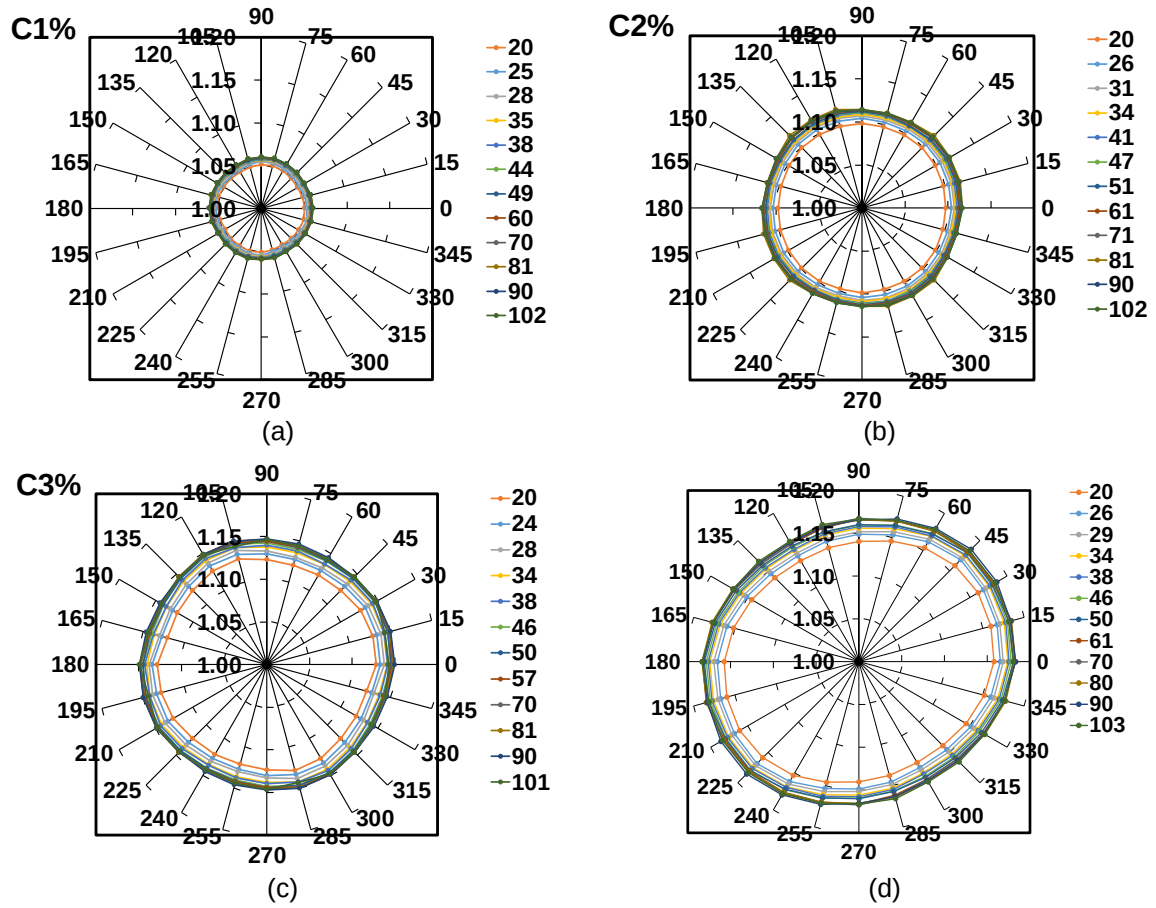


Figure 88. Relative magnetic permeability in cylindrical specimens, C1% (a), C2% (b), C3% (c) and C4% (d).

6.5.3. FIBRE CONTENT INDICATOR

The results of mean relative magnetic permeability ($\mu_{r,mean}$) as a function of angle in all specimens is illustrated in Figure 89.

As it is shown in Figure 89, $\mu_{r,mean}$ is increasing by the increasing of the fibre content and does not vary with the angle.

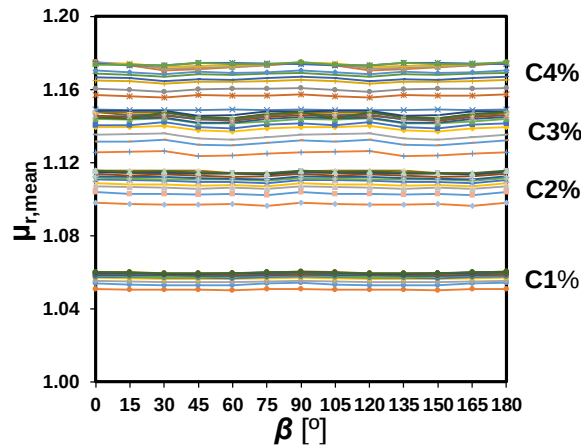


Figure 89. Mean relative magnetic permeability in all cylindrical specimens.

As can be observed from Figure 89, $\mu_{r,mean}$ is increasing linearly and in proportion with the fibre content in C1%, and C2% ; however, for the other specimens with the fibre dosages of 3% and 4% $\mu_{r,mean}$ is not increasing proportionally with the fibre content

In order to identify the exact thickness up to which the inductance results are affected, the inductance changes (ΔL) with the changes of height (ΔH_u) as a function of height (h_u) are illustrated in Figure 90 (a), and the mean inductance results (L_{mean}) as a function of height (h_u) are represented in Figure 90 (b).

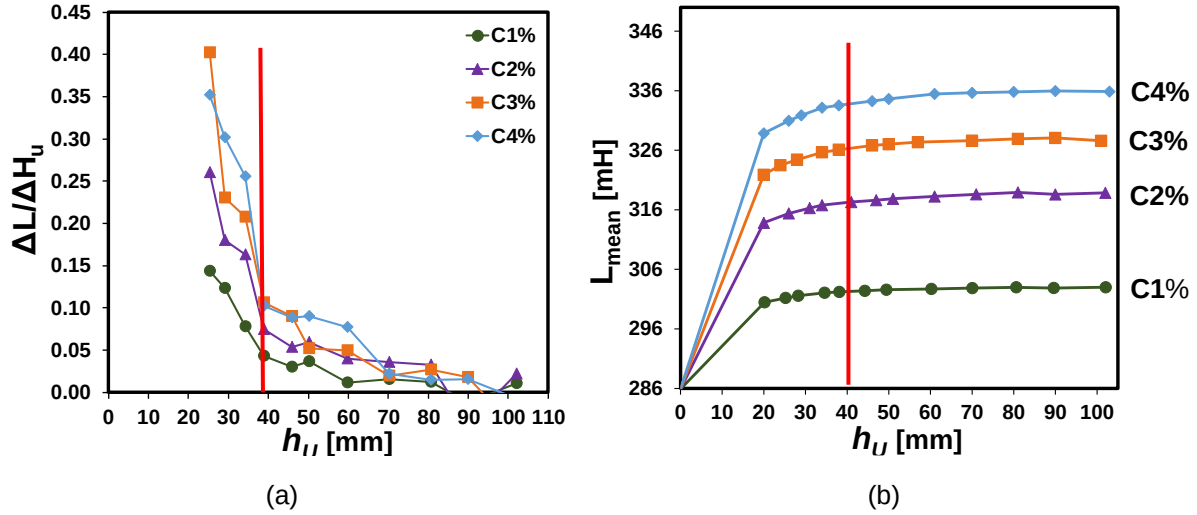


Figure 90. Tangent of inductance changes with height (a), mean inductance changes as a function of height (b).

As can be observed from Figure 90 (b), slight changes (approximately 5%) in inductance results started from the height between 60-70 mm for C3% and C4% and in between the height of 50-60 mm for the specimens of C1% and C2%. However, for all the specimens higher changes of almost 10 % started approximately from the height of 40mm. Consequently, it can be concluded that the results of the NDT measurements done by probe on the specimens, are affected up to the height of 40 mm. In other words for the heights higher than 40 mm, the inductance results do not change significantly.

Based on the evaluated results, mean relative magnetic permeability as a function of fibre content (named as fibre content indicator) is represented in Figure 91 for all the specimens including all thicknesses.

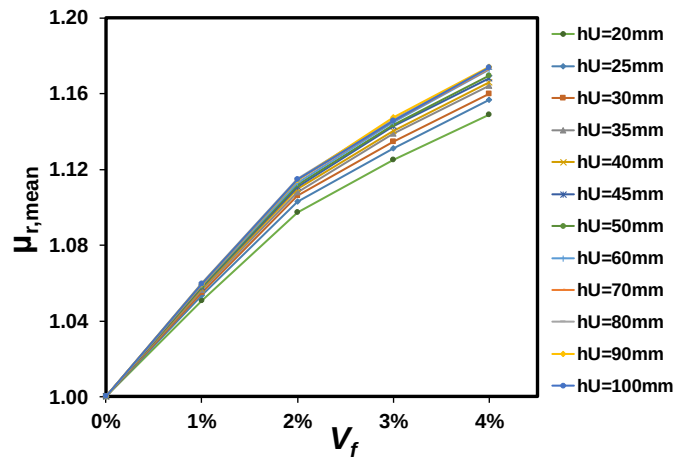


Figure 91. Fibre content indicator factor for all the specimens considering all the thicknesses.

According to Figure 91, the fibre content indicator factor is not following the expected pattern of increasing linearly by increasing the fibre content. A significant variation in the mean relative magnetic permeability is observed in C3%, and C4%. Moreover, the results of fibre content indicator of the cylindrical specimens only for the thickness of 30 mm are compared with the results of fibre content indicator in the horizontal random plate specimens (discussed in chapter 5, section 5.5.3) in Figure 92.

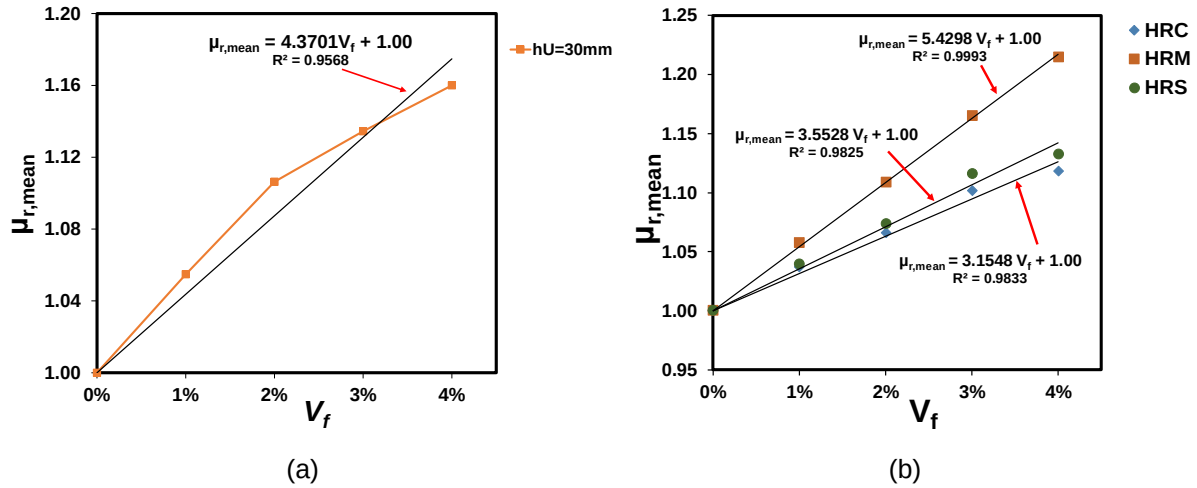


Figure 92. Fibre content indicator factor in cylindrical specimens considering the thickness of 30 mm (a), fibre content indicator factor in horizontal random plate specimens (b).

According to Figure 92, it can be observed that in cylindrical specimen, the mean relative magnetic permeability does not follow the linear relation with the fibre content. Moreover, the calibration lines in cylindrical specimen and the HRM plate specimens do not follow the same pattern and equation. A theory can be proposed in a way that in cylinders (specimens with larger heights) in comparison to the plates (specimens with short heights) the fibre content indicator results can be dependent on the third direction measurements.

6.5.4. FIBRE ORIENTATION INDICATOR

Fibre orientation indicator “ $(\rho_i - \rho_j) (\%)$ ” which is computed for recognizing the preferential orientation of the fibres, and is calculated according to Eq. (25) (discussed in detail in chapter 3, section 3.4) and is represented in Figure 93 for all the specimens.

Positive values of fibre orientation factor indicate that the fibres are oriented along i direction while the negative values prove the orientation of the fibres along j direction (perpendicular to i direction). Moreover, the results close to zero indicate no preferential direction, which is called random.

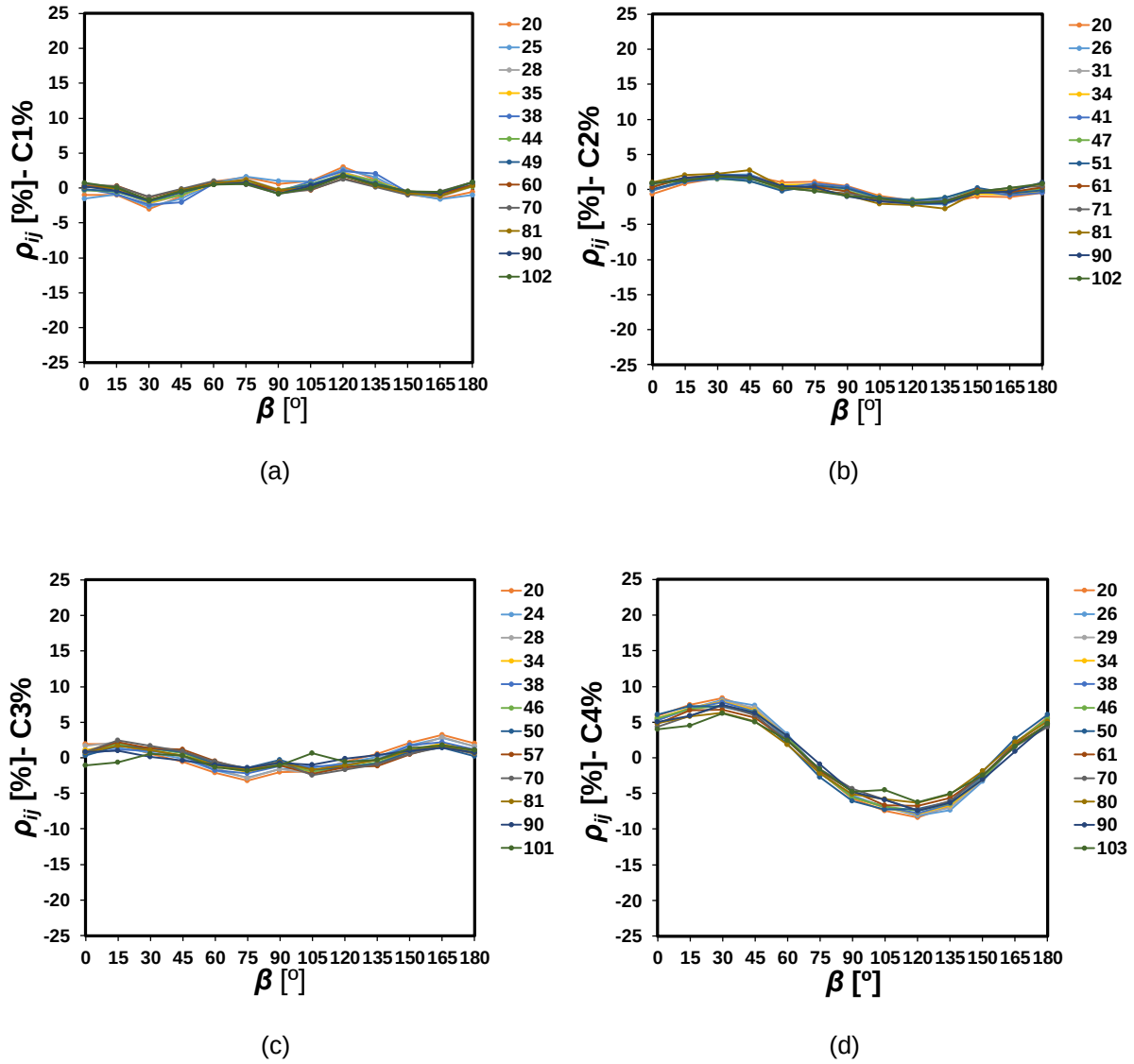


Figure 93. Fibre orientation indicator factor in cylindrical specimens of C1% (a), C2%(b), C3% (c), and C4% (d).

As it can be observed from Figure 93, the results of the fibre orientation indicator is almost very close to zero in all specimens except C4%. In C4% slight orientation along some directions can be observed. This incident can be occurred during casting process in which the flow of the mortar caused some orientations in fibres.

6.6. CONCLUSIONS

- According to the thickness effect as the objective of the present work, it is concluded that the inductance results are affected with the fibres, up to the thickness of around 40mm ($h_u < 40\text{mm}$) in all the specimens.
- According to the fibre content indicator results, it is considered that the inductance does not increase linearly as the fibre content increases, which is probably caused by the 3D distribution of the fibres in these thick cylindrical specimens.

- Overall, the third direction measurements in cylindrical specimens can have impact on the results. Due to the larger heights of cylindrical specimens (100mm) in comparison to the small plates (thickness of 30mm), the fibres might not represent the same in-plane orientations as in the small plates.
- As a limitation of the current study, no measurements of the inductance were taken in the third direction in each stage of the experimental campaign. However, it can be suggested to cut the specimens in the last stage (the height of 20mm), into small cubic specimens and get the third direction inductance measurements by using the set-up described in chapter 4 (small cubic specimens). However, it has to be taken into account that the results would be only useful for the height of 20mm, and cannot be representative of the whole area.

7

CONCLUSION

7.1. FINAL CONCLUSIONS

According to the objectives of the present work, which was assessing and evaluating the influence of key factors on the inductance measurements obtained using magnetic NDT method previously developed at FEUP, different experimental campaigns were carried out for each key factor as described in the previous chapters. This chapter presents the main conclusions derived from the experimental tests and proposes future studies to further develop this research line.

Due to the objectives of Chapter 4, which was assessing the influence of the third direction measurements on UHPFRC elements, some significant results were derived. By comparing the fibre content indicator results of 2D and 3D measurements, it was noticed that the fibre content indicator is higher in 2D than in 3D measurements. It was expected for oriented specimens since the inductance results of X direction had higher values; however, for random specimens theoretically it was expected to have almost same fibre content indicator of 3D measurements.

Based on the obtained results, it is concluded that the third direction measurements should not be neglected.

As a limitation of this work, was not being able to achieve to the information related to the size of the fibres inside the specimens. Moreover, in some of the surfaces of the specimens, it was not possible to establish perfect contact in between specimens and probe during measurements, since there was an air gap originated by shrinkage on the surfaces.

From the experimental program described in Chapter 5, aiming to assess the impact of different surfaces and casting directions in the inductance results, it was concluded that relative magnetic permeability in horizontally cast specimens (both random and oriented) had higher values in moulded surfaces than in cast surfaces. Moreover, even by smoothing the cast surfaces (eliminating air gap) still the moulded surfaces exhibited higher inductance results than the smoothed surfaces. In this case, it was concluded that some fibre sedimentation might have occurred, moving more fibres to the bottom part of the specimens. Further studies need to be carried out to clarify this aspect, for instance by using image analysis technique.

Moreover, in random specimens, relative magnetic permeability in moulded surfaces cast horizontally had higher values than the specimens cast vertically. This phenomenon could be due to the direction of the casting together with the sedimentation of the fibres.

Additionally, in specimens cast horizontally, moulded surfaces had higher values in random specimens than the moulded surfaces in the oriented specimens. A possible explanation for this, was the existence of the magnetic field during casting in oriented specimens, which prevented the sedimentation of the fibres.

In random specimens cast vertically, both surfaces had almost same magnetic permeability results, which proved that the casting direction has noticeable impacts on the results rather than the absence of air gap.

According to the objective of Chapter 6, which was focusing on the thickness effect in cylindrical specimens, notable outcomes were derived. It was concluded that, the inductance results are affected with the fibres, up to the thickness of around 40mm ($h_u < 40\text{mm}$) for the specimens with different fibre dosages in the range between 1%- 4%.

Furthermore, due to the fibre content indicator results, it was considered that the inductance does not increase linearly as the fibre content increases, which is most probably caused by the 3D distribution of the fibres in these thick cylindrical specimens.

Overall, the third direction measurements in cylindrical specimens could have impact on the results. Due to the larger heights of cylindrical specimens (100mm) in comparison to the small plates (thickness of 30mm), the fibres might not represent the same in-plane orientations as in the small plates.

7.2. FUTURE DEVELOPMENTS

As future developments concerning the assessment of key factors influencing on NDT measurements it is suggested to study the effect of rebars being used in concrete structures on the inductance measurements and assess how its effect can be eliminated not to influence the proposed fibre content and orientation indicators.

Due to the results related to the thickness effect, and surface effect achieved in the present work, the influence of the rebars used in different heights in plain concrete, being strengthened by thin UHPFRC layers or not, can be discussed. Moreover, the effect of important parameters related to the rebars; like rebar diameter and the spacing between the rebars could be assessed deeply.

In addition, to fill the knowledge gap related to the 3D measurements, it can be suggested to focus on this area by using numerical analysis. The analysis could be done using specific Engineering software application such as Maxwell Ansys. Maxwell Ansys is a software used in Electrical Engineering field, in which the set-up and specimens can be simulated. Moreover, the impact of the size of the specimens and the probe can be studied by using this software.

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APPENDIX

Table A 1. Inductance results (L) for horizontal oriented plates of Mix 1 and Mix 2.

L Horizontal Oriented (mH)						
HO1				HO2		
$\beta[^\circ]$	HOC1	HOM1	HOS1	HOC2	HOM2	HOS2
0	298.16	301.23	299.01	310.43	316.28	313.40
15	297.75	301.17	298.63	310.40	315.92	312.89
30	296.85	300.44	297.64	309.03	314.24	310.99
45	295.74	299.18	296.33	306.63	312.32	307.94
60	294.70	298.13	295.28	304.33	310.13	305.68
75	294.07	297.23	294.57	302.84	308.18	304.31
90	293.86	296.81	294.38	302.06	307.37	303.42
105	293.87	297.10	294.66	302.38	307.76	303.71
120	294.59	297.79	295.42	303.76	309.42	305.00
135	295.52	298.86	296.50	306.12	311.30	307.29
150	296.60	299.84	297.81	308.72	313.50	310.01
165	297.48	300.70	298.79	310.35	315.16	312.20
180	298.06	301.27	299.00	311.45	316.21	313.47
air	286.05	286.00	286.04	286.09	286.08	286.06

Table A 2. Inductance results (L) for horizontal oriented plates of Mix 3 and Mix 4.

L Horizontal Oriented (mH)						
HO3				HO4		
$\beta[^\circ]$	HOC3	HOM3	HOS3	HOC4	HOM4	HOS4
0	322.75	327.44	325.49	328.99	342.63	332.31
15	322.09	327.47	324.55	328.44	341.54	331.30
30	319.89	325.93	321.89	326.04	338.03	328.85
45	316.45	323.07	318.66	322.51	334.27	325.17
60	313.62	319.60	315.65	319.11	330.60	321.29
75	312.22	317.19	313.79	316.44	328.16	318.41
90	311.66	315.83	312.99	316.46	326.12	318.16
105	311.95	315.83	313.25	316.88	326.24	319.71

120	312.47	317.20	315.04	318.93	328.13	322.10
135	314.95	319.46	317.75	321.98	331.57	325.09
150	317.91	322.82	321.11	326.45	336.29	328.66
165	320.77	325.45	324.05	328.30	340.40	331.57
180	322.73	327.15	325.16	328.97	342.49	332.57
air	286.08	286.19	286.07	286.12	286.21	286.11

Table A 3. Inductance results (L) for horizontal random plates of Mix 1 and Mix 2

L Horizontal random (mH)						
$\beta[^\circ]$	HR1			HR2		
	HRC1	HRM1	HRS1	HRC2	HRM2	HRS2
0	295.04	300.95	295.87	305.84	318.73	308.30
15	295.46	301.00	296.28	305.16	317.70	307.37
30	295.77	301.58	296.50	304.46	317.08	306.51
45	296.33	302.41	297.16	304.00	316.49	305.82
60	296.89	303.25	297.54	303.68	315.07	306.16
75	297.44	303.54	298.07	303.60	314.83	305.96
90	297.96	303.67	298.74	303.53	315.27	305.80
105	297.54	303.04	298.18	303.63	316.74	305.60
120	296.60	302.81	297.50	304.84	318.28	306.25
135	295.73	301.88	296.61	305.67	318.74	307.65
150	295.28	301.50	296.09	306.36	319.34	308.34
165	295.11	301.22	295.88	306.14	320.07	308.22
180	295.09	301.02	295.91	305.93	319.25	308.13
air	285.87	285.90	285.99	285.92	285.94	286.00

Table A 4. Inductance results (L) for horizontal random plates of Mix 3 and Mix 4.

L Horizontal random (mH)						
$\beta[^\circ]$	HR3			HR4		
	HRC3	HRM3	HRS3	HRC4	HRM4	HRS4

0	311.24	329.08	315.38	316.17	346.50	319.20
15	311.99	328.52	315.96	316.94	347.78	319.56
30	312.53	329.16	316.47	317.37	347.28	321.92
45	313.76	332.57	317.44	319.49	348.25	323.86
60	315.65	335.49	319.67	321.85	348.98	326.52
75	318.06	336.95	322.07	323.09	348.74	328.23
90	318.84	337.25	323.13	323.35	348.29	328.64
105	318.17	337.43	322.47	322.27	348.53	327.15
120	316.19	336.22	320.39	321.09	348.66	324.53
135	314.17	333.81	318.48	318.99	348.94	321.97
150	311.62	331.84	315.60	318.06	347.39	321.14
165	310.88	330.76	314.26	316.56	346.92	319.45
180	311.30	329.14	315.31	316.13	347.26	319.25
air	285.94	285.97	286.01	285.97	285.97	286.00

Table A 5. Inductance results (L) for vertical random plates of Mix 1 and Mix 2.

L Vertical random (mH)				
β [°]	VR1		VR2	
	VRML1	VRMR1	VRML2	VRMR2
0	299.87	298.73	312.84	313.82
15	300.16	298.83	311.96	313.38
30	300.11	298.87	310.72	312.36
45	299.87	298.75	309.84	311.75
60	299.52	298.75	309.20	310.79
75	299.12	298.72	309.10	310.48
90	298.74	298.93	309.79	310.83
105	298.85	298.88	310.62	311.71
120	298.98	298.97	311.79	312.26
135	299.36	298.78	312.45	312.87
150	299.69	298.58	313.13	313.29
165	299.62	298.56	313.63	313.51

180	299.88	298.72	312.92	313.83
air	285.92	285.94	285.95	285.96

Table A 6. Inductance results (L) for vertical random plates of Mix 3 and Mix 4.

L Vertical random (mH)				
VR3			VR4	
$\beta[^\circ]$	VRML3	VRMR3	VRML4	VRMR4
0	321.54	322.24	334.32	337.33
15	321.92	322.87	333.84	336.48
30	322.15	322.83	332.36	335.41
45	322.08	322.82	332.53	333.79
60	322.20	322.96	333.08	332.22
75	321.91	322.64	333.44	330.61
90	322.37	322.41	333.38	330.08
105	321.87	322.78	332.47	329.97
120	321.50	323.02	331.84	330.75
135	321.37	322.99	331.53	332.32
150	321.29	322.67	332.75	334.58
165	321.50	322.11	334.17	336.23
180	321.60	322.46	334.70	337.33
air	285.96	285.99	285.99	286.01

Table A 7. Inductance results (L) for cylindrical specimens of C1%.

L (mH)- C1%												
Total thickness (mm)												
$\beta[^\circ]$	20	25	28	35	38	44	49	60	70	81	90	102
0	300.4	301.2	301.6	302.2	302.2	302.4	302.5	302.8	303.0	303.1	303.0	303.2
15	300.3	301.0	301.5	302.0	302.1	302.3	302.5	302.8	302.9	303.0	302.9	303.0
30	300.0	300.7	301.1	301.6	301.7	302.0	302.2	302.4	302.5	302.6	302.5	302.6

45	300.3	300.8	301.3	301.8	301.9	302.1	302.4	302.6	302.7	302.8	302.6	302.8
60	300.5	301.2	301.6	302.0	302.2	302.5	302.6	302.8	302.9	303.0	302.9	303.0
75	300.8	301.6	301.8	302.2	302.4	302.6	302.8	302.9	303.0	303.2	303.0	303.2
90	300.7	301.6	301.7	302.1	302.3	302.5	302.6	302.8	302.9	303.1	302.9	303.0
105	300.6	301.3	301.6	302.1	302.4	302.5	302.7	302.7	302.8	303.0	303.0	303.0
120	300.9	301.5	301.8	302.3	302.5	302.6	302.9	302.8	302.9	303.2	303.1	303.2
135	300.6	301.3	301.6	302.1	302.5	302.5	302.6	302.7	302.8	302.9	302.8	302.9
150	300.2	301.0	301.4	301.9	302.0	302.2	302.4	302.5	302.6	302.7	302.7	302.8
165	300.3	301.1	301.4	302.0	302.1	302.3	302.5	302.6	302.8	302.8	302.8	303.0
180	300.5	301.3	301.8	302.3	302.4	302.6	302.8	302.9	303.2	303.2	303.2	303.3
air	286.0	285.9	285.9	285.9	285.9	285.9	285.9	285.9	285.9	285.9	285.8	285.9

Table A 8. Inductance results (L) for cylindrical specimens of C2%.

L (mH)- C2%												
Total thickness (mm)												
$\beta[^\circ]$	20	26	31	34	41	47	51	61	71	81	90	102
0	313.9	315.6	316.5	317.0	317.5	318.0	318.1	318.6	319.1	319.4	319.0	319.3
15	314.1	315.8	316.8	317.2	317.8	318.1	318.4	318.7	319.0	319.8	319.2	319.3
30	314.3	316.0	316.7	317.4	317.9	318.1	318.5	319.0	319.2	319.8	319.3	319.6
45	314.3	315.9	316.6	317.2	317.7	318.0	318.1	318.8	319.1	320.0	319.1	319.3
60	314.1	315.5	316.4	316.9	317.3	317.6	317.6	318.1	318.6	318.8	318.6	318.7
75	313.9	315.4	316.2	316.8	317.3	317.5	317.8	318.2	318.4	318.6	318.4	318.5
90	314.2	315.8	316.5	317.1	317.6	317.7	318.1	318.4	318.5	318.7	318.4	318.7
105	313.6	315.0	316.0	316.5	317.1	317.2	317.6	317.6	318.1	318.4	318.1	318.4
120	313.4	314.7	315.8	316.3	316.9	317.1	317.4	317.8	318.0	318.3	318.0	318.4
135	313.2	314.6	315.6	316.1	316.7	317.2	317.4	317.7	317.9	318.2	317.8	318.2
150	313.6	315.2	316.2	316.5	317.1	317.6	317.7	318.0	318.5	318.6	318.3	318.6
165	313.3	315.0	315.9	316.3	316.8	317.2	317.4	317.9	318.5	318.5	318.2	318.7
180	313.9	315.6	316.5	317.0	317.3	317.8	318.0	318.6	318.9	319.2	319.1	319.3
air	286.0	286.0	285.9	285.9	285.9	285.9	285.9	285.9	285.9	286.0	285.9	286.0

Table A 9. Inductance results (L) for cylindrical specimens of C3%.

L (mH)- C3%												
Total thickness (mm)												
$\beta[^\circ]$	20	24	28	34	38	46	50	57	70	81	90	101
0	322.7	324.0	325.3	326.2	326.3	327.4	327.5	327.9	328.5	328.5	328.6	326.9
15	322.8	324.2	325.5	326.6	326.6	327.8	327.8	328.4	328.7	328.8	328.7	326.9
30	322.3	324.1	325.2	326.5	326.9	327.7	327.8	328.1	328.5	328.6	328.4	328.4
45	321.2	323.0	324.1	325.4	325.9	326.7	326.9	327.5	327.4	327.6	327.4	327.4
60	320.8	322.3	323.3	324.7	324.8	325.9	326.2	326.6	326.8	326.8	327.2	326.7
75	320.6	322.4	323.1	324.8	325.3	326.0	326.4	326.7	327.0	327.2	327.6	327.1
90	321.3	323.2	324.0	325.4	325.9	326.7	327.2	327.2	327.8	327.9	327.9	327.8
105	321.4	323.1	323.8	325.0	325.6	326.2	326.5	326.5	326.7	327.4	327.8	327.4
120	322.0	323.6	324.4	325.6	326.1	326.6	326.8	327.0	327.1	327.7	328.3	327.9
135	321.6	323.1	324.0	325.2	325.6	326.1	326.2	326.6	326.7	327.4	327.7	327.2
150	322.2	323.6	324.3	325.6	326.2	326.8	326.8	327.0	327.3	327.7	328.1	327.8
165	322.9	324.4	325.3	326.5	327.0	327.4	327.6	328.1	328.3	328.6	328.8	328.6
180	322.7	324.4	325.2	326.2	326.8	327.4	327.4	328.1	328.2	328.5	328.6	328.7
air	286.1	286.0	285.9	285.9	285.9	285.9	285.9	285.9	286.0	286.0	285.9	286.0

Table A 10. Inductance results (L) for cylindrical specimens of C4%.

L (mH)- C4%												
Total thickness (mm)												
$\beta[^\circ]$	20	26	29	34	38	46	50	61	70	80	90	103
0	331.3	333.3	334.2	335.8	336.1	336.9	337.7	338.3	338.2	338.1	338.4	337.6
15	331.8	333.8	334.7	336.3	336.7	337.3	337.9	338.7	338.6	338.6	338.5	337.9
30	332.1	334.1	335.0	336.3	336.6	337.3	337.5	337.9	338.6	338.4	339.3	338.6
45	331.5	334.2	335.0	336.0	336.4	337.2	337.4	337.6	338.1	338.0	339.1	338.3
60	330.0	332.3	333.1	334.3	334.4	335.4	335.2	336.3	336.5	336.5	337.4	337.0
75	327.8	329.9	330.9	332.0	332.5	333.2	333.1	334.5	334.8	334.7	335.4	334.9
90	326.2	328.6	329.3	330.6	331.1	331.6	331.7	333.5	333.9	333.3	333.4	333.6
105	325.5	327.7	328.5	329.7	330.2	330.8	330.9	332.2	332.7	332.9	332.7	333.4

120	325.0	326.8	327.7	328.9	329.3	330.2	330.6	331.3	331.4	332.2	331.9	332.4
135	325.8	327.6	328.6	329.8	330.2	331.0	331.5	332.1	332.2	332.9	332.8	333.4
150	327.5	329.3	330.4	331.5	332.0	332.5	333.3	333.9	334.1	334.6	334.4	334.5
165	329.5	331.7	332.7	334.0	334.5	335.1	335.7	336.4	336.4	336.8	336.3	336.4
180	331.1	333.3	334.4	335.8	336.3	336.9	337.6	338.2	338.2	338.5	338.1	338.4
air	286.1	286.0	285.9	286.0	285.9	286.0	286.0	285.9	286.0	286.0	286.0	286.0
