Assessment of Fibre Content and Orientation in SFRC with the Inductive Method. Part 1: Theoretical Basis of the Method and Study of the Influence of the Type of Coil and Temperature on its Accuracy

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Abstract
The inductive method is a non-destructive test which is capable to estimate both the fibre orientation and the fibre content in steel fibre reinforced concrete (SFRC) samples by the means of a coil and an impedance analyser. In this study, the theoretical basis of the method and the equations for assessing the content and orientation of fibres are given. Finite Element simulations are performed to estimate the parameters of the equations. An experimental program is conducted to evaluate the influences of two different coils and the temperature on the test. The results show that good accuracy and repeatability are obtained with both coils and no correction is needed for consideration of the impact of temperature.

Keywords: Fibre reinforced concrete (FRC), inductive method, fibre content, fibre orientation, influence of temperature, type of coil

1. Introduction

Fibre-reinforced concrete (FRC) is one of the most relevant innovations in the field of concrete technology. The addition of short, discrete fibres provides enhanced properties to this composite cement-based material. In the hardened state, both post-cracking residual strength of the material and its toughness are significantly increased. This enhanced behaviour is influenced mainly by the amount of fibres crossing a crack effectively and the bond and strength properties of the fibres used [1, 2].

In this sense, several authors have shown the influence of the orientation of the fibres on the residual strength of the material [3, 4]. The anisotropic orientation of fibres in the hardened state may occur as a result of the different stages and processes that FRC undergoes from mixing to hardening. For this reason, the anisotropy due to the dispersion and orientation of fibres has to be taken into account when characterizing the mechanical behaviour of the material.

This fact highlights the necessity for new non-destructive methods for quality control of FRC, combining practicality and economy with efficiency. In order to overcome this drawback, a control method, so called the Inductive Method (IM) was developed on the basis of the UNE 83512-1 regulation [5] taking advantage of the different magnetic permeability between concrete and steel. The method is a robust and simple test to assess the content and the distribution of steel fibres in FRC which represents an advance towards the characterization and the quality control of SFRC.

The objective of the present paper is to provide the theoretical basis of the method. Different experimental programs and finite element numerical simulations are conducted to evaluate the accuracy of the method and to validate the proposals. Additionally a comparison between different types of coils as well as the influence of temperature of each measurement will be addressed. It represents an advance towards the characterization and the quality control of SFRC.

2. The inductive method

The inductive method is a non-destructive test which is based on measuring the inductance change produced when a SFRC sample interacts with a magnetic field (B). It is capable to estimate both the fibre content and the fibre orientation in FRC samples. It was developed by researchers of the Polytechnic University of Catalonia [6 – 8]. It uses an impedance analyser which produces an electrical flow through a coil, thus inducing a magnetic field around it. If a sample is put into the coil, the ferromagnetic nature of the fibres increases the magnetic permeability of the medium and an inductance variation (ΔL) is measured with the analyser.

Different ΔL are obtained after placing the sample into the coil in different positions. For cubic specimens, measurements of inductance are performed for the 3 main directions (X, Y and Z) perpendicular to the faces of the samples (Figure 1.a). In the case of cylindrical samples, measurements are done in 4 positions: the vertical one (Z) (Figure 1.b) and 3 horizontal positions (Figure 1.c) corresponding to the angles of 0, 45 and 90º (X, λ and Y respectively). Further information is given in [8].

According to the theoretical foundations, the method can be applied regardless of the coil if the distribution of the magnetic field is known. The first attempts at implementation were done by using a square-shaped coil [6]. The authors presented a square-shaped cross section with 17 cm of side and it was made by a pair of coils connected in parallel and separated 7.5 cm. Each one was made with 1,600 m of 0.2 mm diameter copper cable, resulting in a total of 2,354 turns (Figure 2.a).

In order to obtain a more homogeneous distribution of the magnetic field, an additional circular coil was used in [7, 8]. It consisted of two spirals separated 13 cm and also configured in parallel. Each of them had a circular cross section with 25 cm of interior diameter and was made of 1,200 turns of copper cable of 0.3 mm of diameter (Figure 2.b). The electrical current input and the inductance measurements were performed with the equipment AGILENT LCR 4263B (Figure 2.c). It was set with an electrical alternating current, a frequency of 1 kHz and a voltage of 1 V.

3. Theoretical basis

3.1. Prediction of the content of fibres

Cavalaro et al. [7] demonstrated that the sum of the ratio between the inductance measurement in the X, Y and Z axis and a corresponding constant $B_{V,i}$ holds a linear relation with the content of fibres (Eq. 1). The parameter $B_{V,i}$ represents the integral of the magnetic field over the volume of the sample. Such parameter does not depend on the fibre used, and it is constant if the specimen is always placed in the same position and the coil is the same. Furthermore, in cubic specimens $B_{V,x}$, $B_{V,y}$ and $B_{V,z}$ are equal due to the symmetry of the sample.

The proportionally constant β depends of the fibres used. It can be determined by dividing the fibre content weighted after crushing a specimen and the corresponding measured value of equivalent inductance (ΔL_T). Thus, it is obtained the slope of the straight line that passes through the origin of the coordinate system and relates ΔL_T and the fibre content (c_f). Notice that β should be the same for any shape of specimen and concrete type.

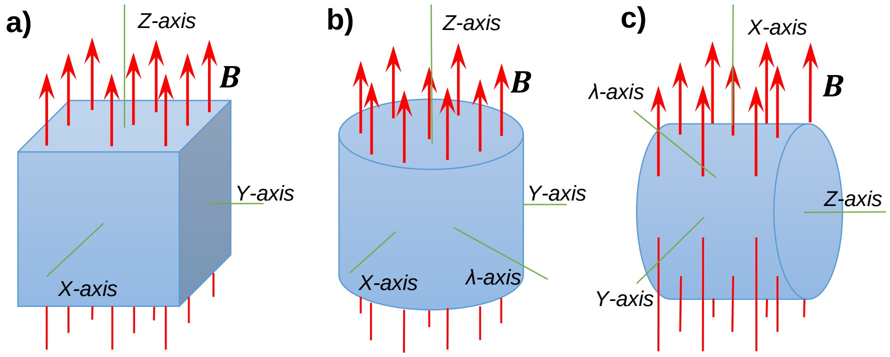


Figure 1. Position of the specimens inside the coil: cubic specimen (a) and cylindrical specimen (b, c).

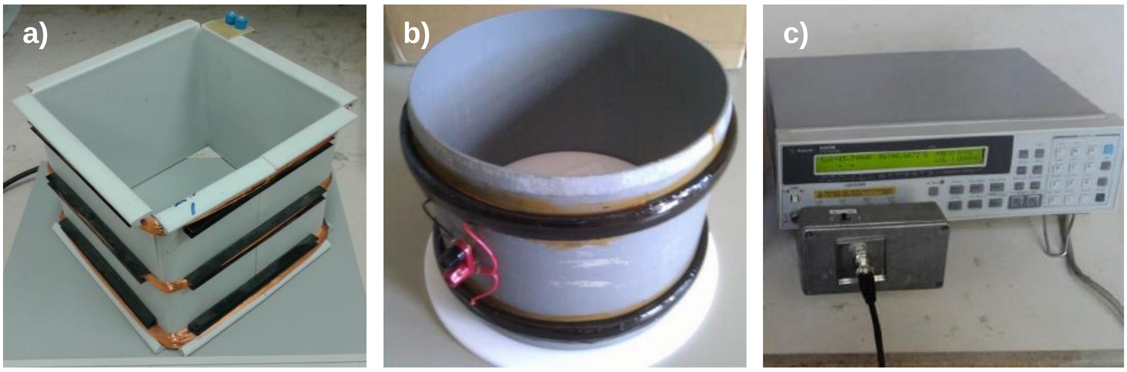


Figure 2. Square-shaped coil (a). Circular coil (b). Measurement equipment (c).

3.2. Prediction of the orientation of fibres with the circular coil

The orientation number (η_i) corresponds to the average of the cosine of the angle formed between the fibres and the line parallel to the axis i [9]. It can be assessed by the means of Eq. 2. The parameter γ corresponds to a shape factor related with the aspect ratio of the fibres and may be obtained by the ratio between the inductance of a single fibre perpendicular and parallel to the magnetic field. The parameters μ and ϑ depend on the properties of the coil used and the shape of the specimen. Due to the complexity of obtaining their values analytically, they have been calculated through different experimental programs and electromagnetic finite element (FE) numerical simulations.

The FE model considered both the magnetic field produced by the circular coil and the dispersed fibre inside the coil. It was validated with experimental results by using hand-made specimens with known fibre content and orientation. Square and circular shapes of non-magnetic cardboard were cut and glued together in order to form four cubes with an edge length of 150 mm (Figure 3.a) and one cylindrical specimen with 150 mm of diameter and 150 mm of height (Figure 3.b). It is worth stressing that the magnetic permeability of the fibres is several times bigger than those of the cardboard sheets and plain concrete, so the results with the cardboard specimen should be approximately the same to the obtained if a concrete specimen with identical fibre orientation is used.

$$C_f = \beta \cdot \sum_{x,y,z} \frac{\Delta L_i}{B_{V.i}} = \beta \cdot \Delta L_T \tag{1}$$

$$\eta_i = \theta \cdot \sqrt{\frac{\Delta L_i \cdot (1 + 2 \cdot \gamma) - \Delta L_T \cdot B_{V.i} \cdot \gamma}{\Delta L_T \cdot B_{V.i} \cdot (1 - \gamma)}} - \mu \tag{2}$$

A total of 1260 SFRC specimens were simulated with the magnetic field acting in the X, Y and Z directions, thus reproducing the procedure conducted during the test. The simulations considered both cylindrical and cubic geometries of cast specimens and extracted cores. Three values of γ (0.000, 0.025 and 0.050) were also included into the study. A shape factor of 0.000 represents a theoretical situation in which the diameter of the fibre is negligible while a value of 0.050 is representative of the fibre used in the experimental program. Table 1 presents the parameters for the assessment of the fibre content and orientation in any cylindrical and cubic specimens. It is important to remark that they remain constant regardless of the concrete mix, fibre content and type.

4. Influence of the type of coil and the temperature

4.1. Experimental program

A total of 22 cubic specimens with 150 mm of edge were cast with 6 concrete mixes, using 2 types of concretes (conventional and self-compacting) with 3 nominal fibre contents (30, 45 and 60 kg/m^3) each. They were tested with the inductive method and then crushed to assess the actual fibre content. The compositions of the concrete mixes and their fresh state properties are presented in Table 2.

The steel fibres used in the SFRC were BASF Masterfiber 502 with a circular cross-section, hooked ends, 50 mm of length and an aspect-ratio equal to 50. Batches of 120 litres were produced using a 250 litres vertical mixer, which resulted enough to cast all samples of the same mix. For each mix, 4 specimens were produced according with EN 12390-2 [10].

Figure 3. Cardboard cubic (a) and cylindrical (b) specimens.

Measurements of inductance were taken positioning the cubes in the three directions. In order to evaluate the repeatability of the method, this procedure was repeated several times in the same specimen. The inductance measurements were performed with the two coils and followed the procedure defined in Torrents et al. [6]. Finally, the estimation of the fibre content was conducted for 10 specimens according to the standard EN 14721 [11]. The specimens were cracked using a hydraulic press and then crushed in a grinding machine. Afterwards, the fibres were manually separated with the help of a magnet and weighted.

Table 1. Constant parameters of the circular coil for cylindrical and cubic samples

Shape	Size	Parameter				
		$B_{V,x}$	$B_{V,y}$	$B_{V,z}$	μ	ϑ
Cylindrical	*Φ100 x 100*	536	536	538	0.085	1.03
	Φ150 x 150	1,789	1,789	1,809	0.085	1.03
Cubic	100 x 100 x 100	695	695	695	0.100	1.03
	150 x 150 x 150	2,342	2,342	2,342	0.100	1.03

4.2. Influence of the type of coil

Figure 4.a provides the equivalent inductance (ΔL_T) measured using the two coils and the content of fibres (c_f) weighted for the 10 specimens. Both cases present a high value of the coefficient of determination (R^2), thus indicating the high accuracy of the method. Furthermore, for the fibre used the relation of proportionality of the square-shaped and circular coil are equal to 0.4746 kg/m^3 and 2.4685 kg/m^3 times ΔL_T respectively, which means that the square-shaped coil is more sensitive to magnetic field changes.

Figure 4.b provides the measured and the estimated content of fibres obtained by using both coils. The average and the standard deviation of the absolute error corresponding to the square-shaped coil are 1.367 kg/m^3 and 0.914 kg/m^3, while for the circular coil their values are 1.197 kg/m^3 and 0.633 kg/m^3, respectively. These small values confirm that the inductive method provides a good prediction of the fibre content with an average error lower than 1.50 kg/m^3, which may be presumed as negligible for practical purposes.

Another important issue is to determine the repeatability of the measurements, which is supposed to depend on the accuracy of the measurement equipment and the user's ability to insert the specimens into the coil in a perfectly centred position. The repeatability was studied under the same combinations of temperature of the point 4.3, repeating a total of 192 measurements of inductance for each individual coil.

The relationship between the results obtained in the first measurement and in the repetitions is presented in terms of inductance in each axis (Figure 5.a) and in terms of the estimation of the content of fibres (Figure 5.b).For the inductance, the repeatability, calculated as the absolute difference between the first measurement and the repetition, is equal to 0.12 mH in the case of the square-shaped coil, while for the circular coil its value is 0.03 mH. The relative error, estimated as the modulus of the difference between the first measurement and the repetition divided by the average of both of them, is equal to 0.37 % and 0.54 % for the square-shaped and the circular coil, respectively. Regarding to the estimation of the fibre content, the repeatability is equal to 0.12 kg/m^3 for the square-shaped coil and 0.20 kg/m^3 for the circular one. These results indicate that the test presents a good repeatability with small average relative errors both for the measurements of inductance and the estimation of the fibre content. Consequently, it is suitable for assessing the fibre rebound in sprayed concrete, as it is presented in [12].

Table 2. Concrete mixes tested

Components	Characteristics	Content (kg/m^3)					
		Conventional			Self-compacting		
Gravel (12/20 mm)	Granite	810			200		
Gravel (5/12 mm)	Granite	404			500		
Sand (0/5 mm)	Granite	817			1200		
Cement	CEM I 52,5 R	312			380		
Water	-	156			165		
Superplasticizer	Glenium TC 1425	2.19			4.56		
Hidratation activator	X SEED	6.24			7.6		
Fibres	Steel fibres	30	45	60	30	45	60
Reference		CC30	CC45	CC60	SC30	SC45	SC60
Slump (mm) according UNE 83503		3	5	3	-	-	-
Flow extent (mm) according EN 206		-	-	-	650	650	670

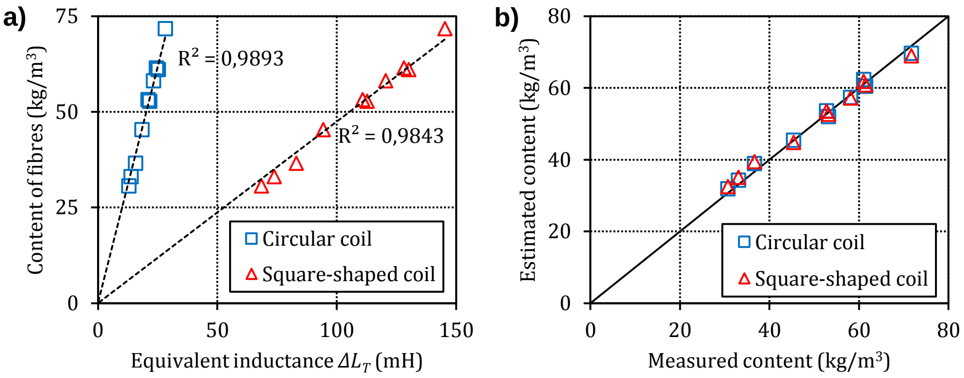


Figure 4. Relationship between: ΔL_T and C_f (a) and measured and estimated C_f (b).

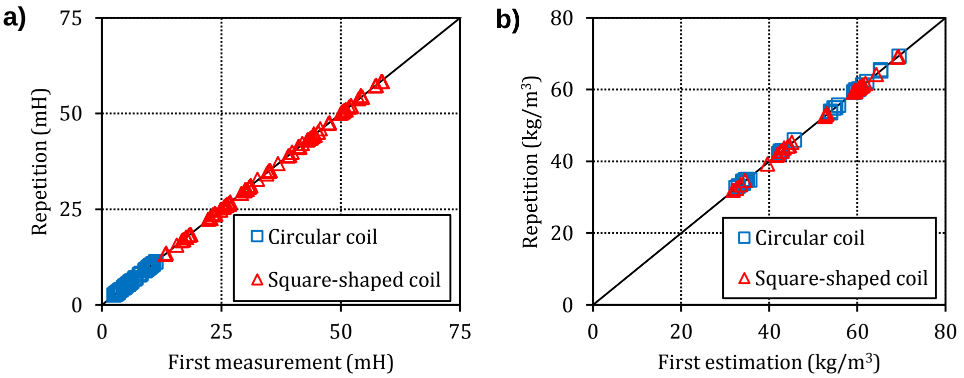


Figure 5. Repeatability of the method for the measurements of inductance (a) and the predicted content of fibres (b).

4.3. Influence of the temperature

The influence of the temperature on the inductive method was studied considering three factors: the equipment, the coils and the specimens. According to the manufacturer, the optimal working temperature of the measurement equipment is 23 ºC, even though the accuracy of the equipment decreases with differences of temperature. On the other hand, the coils are made by copper cables which may expand or contract their length due to thermal variations. Therefore, geometric changes in the coils could be a contributing factor to perturbations in the inductance measurements. Finally, SFRC is constituted by a concrete matrix and steel fibres which present similar thermal expansion coefficients, so temperature may also vary the volume of the specimens. It is suggested that the temperature of the specimens may affect the measurements. In consequence, determining the temperature sensibility of the method is a key issue to ensure its applicability under non-controlled temperature conditions.

The study of the temperature was performed assuming that the coils and the measurement equipment were under the same temperature (ambient temperature), since both usually stay together. The influence of temperature on the equipment and coils was determined under temperatures of 10, 20 and 30 ºC. Similarly, the sensibility of the method to the temperature of the specimens was assessed setting their temperature to 0, 10, 20 and 30 ºC. Also, it is also studied the effects of maintaining both the coils and the equipment and the specimens under temperatures of 10, 20 and 30 ºC. Table 3 shows all the combinations of the studied temperatures. A reference temperature of 20 ºC was defined (Case 5) as a corresponding to laboratory conditions. It is worth remarking that for reaching the studied temperature combinations the equipment, the coils and the specimens were kept in temperature controlled chambers for 24hours.

For all the specimens Table 4 shows the variations of the prediction of the content of fibres compared to the predicted value at the reference temperature ($c_{f,20}$). The left and the right columns cover the results of the square-shaped and the circular coils, respectively. The first row corresponds to the influence of the ambient temperature (cases 2 and 7), the second row presents the results of the influence of the temperature of the specimens (cases 3, 4 and 6) and the last row shows the effects of varying the temperature of the ambient and the specimens (cases 1 and 8).

Regarding to the consequences of the ambient temperature, the magnitude of the error is generally higher at 10 ºC than at 30 ºC, because the precision of the equipment decreases as temperatures moves away from its optimum working temperature (23 ºC). In the cases of the square-shaped coil (Table 4.a) there is no clear tendency on the behaviour of the results, while most of the measurements performed with the circular coil (Table 4.b) induce a positive value of the error.

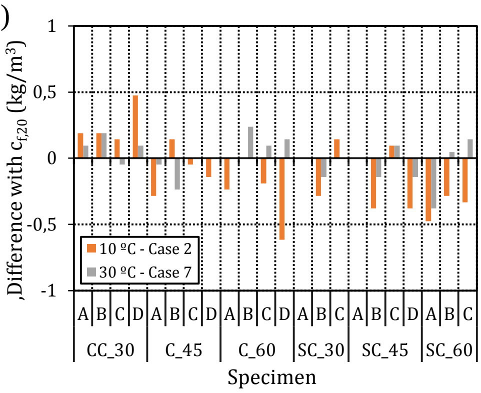
Table 3. Combinations of temperature

Cases	**Temperature (ºC)**	
	Equipment + coils	**Specimens**
1	10	10
2	10	20
3	20	0
4	20	10
5 (*)	20	20
6	20	30
7	30	20
8	30	30

(*) Reference temperatures

On the other hand, when changing the temperature of the specimens the smallest measurements are obtained at 0 ºC and the higher ones for 30 ºC, while for 10 ºC they are mainly slightly lower than at the reference temperature. This behaviour is obtained both for the square-shaped coil (Table 4.c) and for the circular coil (Table 4.d). In consequence, it can be assumed that the predicted value of the content of fibres increases with the temperature of the specimens.

Table 4. Influence of the temperature on the prediction of the fibre content

<table>
<tr><th></th><th>Square-shaped coil</th><th>Circular coil</th></tr>
<tr><td>Influence of the temperature of the ambient</td><td>a)

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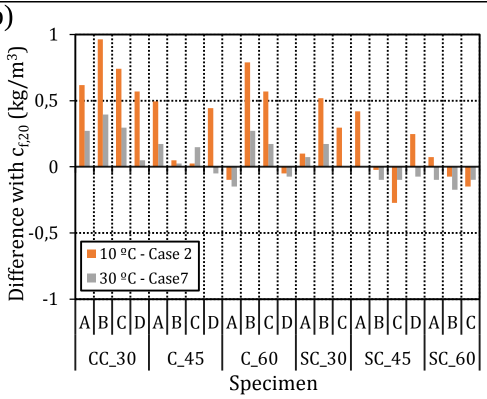
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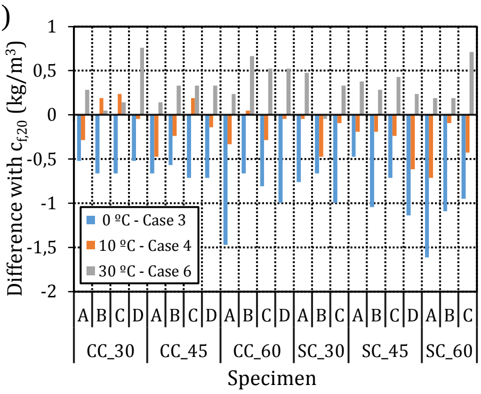
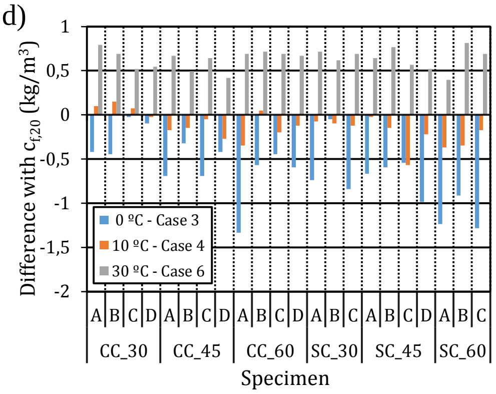
<tr><td>Influence of the temperature of the specimens</td><td>c)

</td><td>d)

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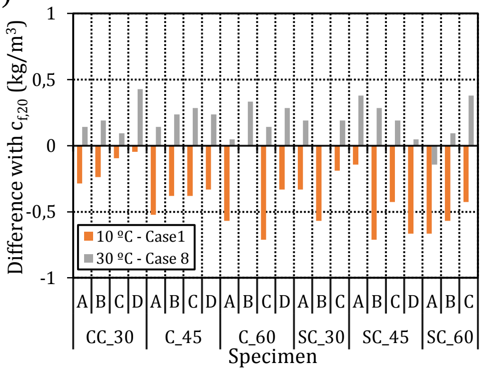
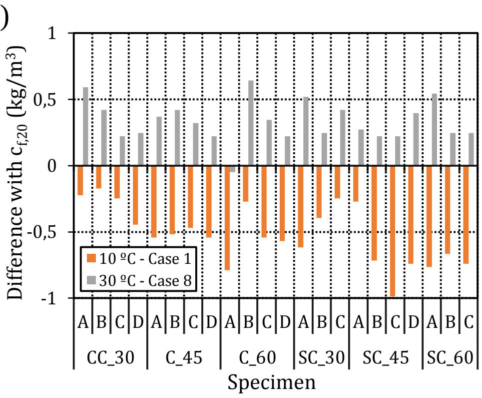
<tr><td>Influence of the temperature of the ambient and the specimens</td><td>e)

</td><td>f)

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Finally, when the temperature of the coils, the measurement equipment and the specimens are variated together, the smallest predictions of the fibre content are also obtained at 0 ºC and the higher ones at 30 ºC. Furthermore, there also is a clear tendency to obtain higher predictions for higher temperatures both in the case of the square-shaped coil

(Table 4.e) and the case of the circular coil (Table 4.f), which may be explained by the effect of the temperature of the specimens.

A graphical summary of the errors induced by the temperature when estimating the fibre content is presented in Figure 6. It shows both the average and the standard deviation of the absolute error between the prediction of c_f in the Case 5 and the other Cases. The horizontal axis indicates the coil and the influence of the ambient temperature (*Amb.*), the specimens and both the ambient and the specimens (*Amb.+spec.*). In all cases the average error of estimation the standard deviation are smaller than 1.0 kg/m^3 and 0.40 kg/m^3, respectively. This allows to affirm that the accuracy of the inductive method is not significantly affected under the studied ranges of temperature. Consequently, no correction is needed to be applied when using the method under temperature conditions different to 20 ºC.

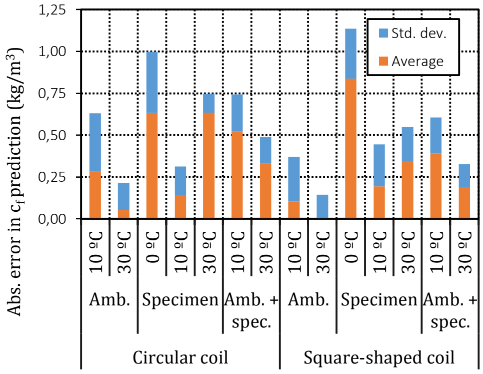

Figure 6. Absolute error in the prediction of fibre content induced by temperature.

5. Conclusions

The results of the study presented confirm that the inductive method is an easy and low-time consumption test to assess the fibre content and orientation in SFRC samples. Regarding to its applicability, the accuracy obtained with two types of coils and the influence of temperature on the method, the following conclusions are derived:

- The content of fibres (c_f) and the orientation number of fibres (η) can be estimated by the means of the measurements of inductance. The equations and the theoretical fundamentals were given for any sample shape and type of steel fibre. Additionally, by means of a FE simulations the required constants have been calculated for 100 mm and 150 mm edge cubic samples and also for ϕ100x100 mm and ϕ150x150 mm cylindrical samples.

- The method presents high accuracy and repeatability when predicting the content of fibres. The average and the standard deviation of the absolute error are 1.367 kg/m^3 and 0.914 kg/m^{3}for the square-shaped coil and 1.197 kg/m^3 and 0.633 kg/m^{3}for the circular coil. On the other hand, the repeatability is equal to 0.12 kg/m^3 for the square-shaped coil and 0.20 kg/m^3 for the circular one. The magnitude of these errors suggests that they may be assumed as negligible for practical purposes.

- The influence of temperature on the method has been experimentally studied with different combination of temperatures ranging from 0 to 30 ºC. The results show that the more is the temperature of the specimens, the bigger is the predicted c_f, while no clear tendency is obtained when varying the temperature of the coils and the measurement equipment. Nevertheless, in all the cases the average and the standard deviation of the absolute error were always less than 1.0 kg/m^{3}and 0.40 kg/m^3 in both coils. These errors may also be assumed as insignificant, so no correction is needed if the method is used under the studied temperature ranges.

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