INFLUENCE OF TEMPERATURE ON THE ASSESSMENT OF FIBRE CONTENT AND ORIENTATION WITH THE INDUCTIVE METHOD

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Abstract

The behaviour of the steel fibre reinforced concrete (SFRC) in highly dependent of the content and the orientation of the fibres. The assessment of these parameters is a necessary step towards the on-site quality control of the material. Several methods are available to perform such assessment, most of them based on the application of magnetic fields. The magnetic properties of the steel fibres are affected by the environmental temperature, which in theory could modify the measurements obtained in the test. The objective of this paper is to evaluate the influence of the temperature on the results of the inductive method developed at the UPC. For that, several FRC cubic samples were produced with 3 fibres contents: 30 kg/m³, 45 kg/m³ and 60 kg/m³. The samples are then tested in a climatic chamber under different room temperatures. The results allow the determination of equation to correct the measurements of the inductive method, thus increasing the reliability of the results obtained.

Keywords: SFRC, content, orientation, inductive method, temperature

1. Introduction

The growing use of Steel Fibre Reinforced Concrete (SFRC) has motivated the development of several new testing methods to characterise the properties of the material. In this context, a great effort has been dedicated towards the assessment of the fibre content, which shows a high repercussion in the behaviour of SFRC. [1-4] Most of the tests developed with that purpose are based on the application of magnetic fields that is influenced by the magnetic response of the steel fibres. [5-6]

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It is known that the magnetic properties of the steel fibres are affected by the environmental temperature, which in theory could modify the measurements obtained in the test. However, little information on the subject may be found in the technical literature. Taking that into account, the objective of this study is to evaluate the influence of the temperature on the results of the inductive method developed at the UPC.

The experimental program conducted in the Laboratory of Structure Technology Luis Agulló at UPC with different concrete types included more than 600 inductance measurements taken for 8 combinations of temperatures of the equipment and of the specimens. The results obtained shed light on the influence of the temperature and allow the determination of an equation to correct the measurements of the inductive method, thus increasing the reliability of the test.

2. Experimental program

2.1 Specimens

In the experimental program, a total of 22 SFRC cubic specimens (15 cm) were cast and tested. From all the specimens, 12 of them were produced with conventional concrete (CC) and the other 10 with self-compacting concrete (SCC). In addition, three dosages (30, 45 and 60 kg/m^3) were considered in each type of concrete. The notation used for each type of concrete and dosage of fibres is presented in Table 1.

Tab.1: Notation for the specimens

Type of concrete	Dosage [kg/m^3]	Notation
Conventional concrete	30	CC_30
	45	CC_45
	60	CC_60
Self-compacting concrete	30	SCC_30
	45	SCC_45
	60	SCC_60

2.2 Materials and concrete mix

A 250 litres vertical mixer was used to produce the concrete. The concrete mix used for the three dosages was the same in the case of the conventional concrete and the SCC. The details of the concrete mix used for each type of concrete are presented in Table 2.

Tab.2: Concrete mix

Components	Characteristics	CC	SCC
		Content [kg/m³]	Content [kg/m³]
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

The steel fibres used were BASF Masterfiber 502 with a circular cross-section and hooked ends. These fibres are made of low carbon steel and are gathered into bundles by water-soluble glue. The main characteristics (provided by the manufacturer) are presented in Table 3.

Tab.3: Characteristics of the fibres

Characteristics	
Tensile strength	Min. 1000 N/mm^2
Length	50 ± 5 mm
Diameter	1.0 ± 0.1 mm
Aspect ratio	50
Fibres/kg	3000

The specimens were cast according to procedure described in the standard EN 12390-2. The specimens were demoulded after 24 hours of casting and they were stored in a heat-curing room in the facilities of the company PROMSA at a temperature between 19 and 21ºC and a relative humidity of 95%.

2.3 Testing method

The equipment used in the inductive method is comprised of two elements: the measurement equipment LCR and the coil. Both components are connected by means of a cable designed specifically for that purpose. These elements are shown in Figure 1.

Fig. 1: a) Coil, b) measuring equipment, c) cable.

The square and discontinuous coil was manufactured with a copper cable of 0.2 mm of diameter and a length of 1600 mm, resulting in a total of 2354 turns. The dimensions of the prismatic plastic element where the coil is placed are 15 x 17 x 17 cm (see Figure 1a).

The inductance measurements were taken with the equipment AGILENT LCR 4263B (see Figure 1b). This equipment allows measuring inductance, capacity and electrical resistivity. Furthermore, it provides the coil with electrical current.

The equipment was set for taking measurements with an electrical alternating current, a frequency of 1 kHz and a voltage of 1 V. Furthermore, the values shown are the result of an average of five measurements in order to avoid errors. Given that the equipment is capable of showing two parameters per measurement, it was decided to register the inductance and the electrical resistivity.

2.4 Temperature rooms

The temperature during the measurements was controlled by using two different climate-controlled rooms. The first room was set to a range of temperatures between 19-21ºC and the second one allows working with temperatures between 0-50ºC. In both cases, the relative humidity remained 80%.

The temperature and relative humidity in the first room was controlled with the portable system (see Figure 2a), connected to an automated equipment that maintained the internal conditions stable. In the case of the second room, the temperature and the relative humidity were controlled by means of a computer and a control panel. Figure 2b shows the entrance of the second room.

Fig. 2: a) Portable control system and b) second room.

2.5 Methodology to assess the influence of the temperature

The self-inductance of a coil depends, among other factors, on its geometric characteristics. Coils are manufactured with copper thread, whose length and geometry vary with temperature. This phenomenon may affect the inductance measurements, thus jeopardizing the reliability of the test by having temperature-dependant results.

Furthermore, according to the specifications of the manufacturer, the accuracy of equipment used is sensible to the temperature. The optimum equipment temperature for measuring is 23ºC, losing sensibility as the difference with that value becomes larger.

Regarding the SFRC specimens, the magnetic properties of the steel fibres are temperature dependent. Even though this variation is small for the temperature range expected in practice, it might not be so small in terms of the inductance measurements. For this reason, the influence of the temperature of the specimens in the inductance was also considered in the study.

Considering the aforementioned factors, it was decided to study different combinations of temperature for the coil, the equipment and the specimens. Particularly, the temperatures considered for the measuring equipment and the coils are 10ºC, 20ºC and 30ºC and for the specimens 0ºC, 10ºC, 20ºC and 30ºC. In order to set a rational combination of such temperatures, the following criteria were considered.

- The coil and the equipment are at the same temperature in all cases, since in real situations they are always in the same location (both in the storage and in the measurement location).

- The temperature of the specimens may influence the inductance measurements. For that purpose, measurements are taken with the equipment and coil at 20ºC and the specimens at 10ºC and 30ºC.
- In order to study the influence of the equipment and coil in the measurements, the combination of equipment and coil at 10ºC and 30ºC and specimens at 20ºC is also considered.

During the experimental program and in view of the evolution of the results, it was considered that an additional temperature for the specimens should be included in the study. Consequently, the measurements were taken also for the cubic specimens at 0ºC. The 8 cases of study resulting from the previous criteria are presented in Table 4.

Tab.4: Cases of study.

Cases	**T .Equipment [ºC]**	**T .Coil [ºC]**	**T .Specimens [ºC]**
1	10	10	10
2	10	10	20
3	20	20	0
4	20	20	10
5	20	20	20
6	20	20	30
7	30	30	20
8	30	30	30

Notice that when the specimens had to be moved from one room to another, these were moved one by one. This means that firstly one specimen was moved to the measurement room, subsequently the measurements were taken and finally another specimen was moved to start the process again. This procedure intends to assure that the variation of temperature would be negligible.

3. Results

3.1 Influence of the temperature of the equipment and the coil

In order to analyse the influence of the temperature of the equipment and the coil in the inductance measurements, these are presented in terms of the sum of the inductance measured in the three directions of the cubic specimen. The reason to consider the sum of the inductance instead of the value of each direction is to easily visualize a possible error tendency in the measurements. For example, if the measurements are always smaller for a temperature A than a temperature B, the difference will be more evident with the sum of the 3 measurements.

The variation in the sum of inductances R_n for a temperature of the equipment and the coil of 10ºC and 30ºC with respect to the measurements for 20ºC is presented in Figure 3. Notice that the temperature of the specimens in all cases is 20ºC.

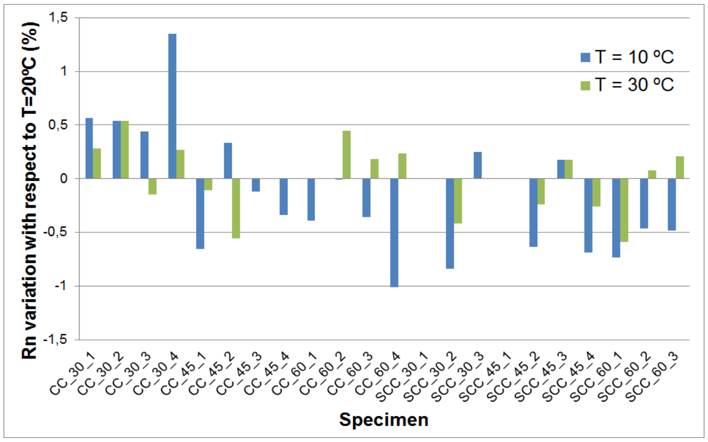

Fig. 3: Variation of the inductance measurements for temperatures of the equipment and the coil of 10ºC and 30ºC with respect to 20ºC.

In view of the results, a clear tendency cannot be observed. The only aspect to highlight is that the errors are bigger for 10ºC than for 30ºC. This was expected given that the optimum temperature for the equipment, according to the manufacturer, is 23ºC and the accuracy decreases as the difference with that temperature increases.

In order to determine if the temperature should be considered in the results of the inductive method, the average error (in terms of percentage) is calculated. The expression in Equation 1 is used to obtain the error. Again, the measurement at 20ºC is taken as a reference.

$$Error(\%) = \frac{|L_{10/30} - L_{20}|}{L_{20}} \cdot 100 \qquad (1)$$

According to Equation 1, the average error and the standard deviation of the error in the measurements are presented in Table 5. Notice that the value of error presented in Table 5 also include other parameters besides the temperature such as the accuracy of the equipment, the slightly variation in the position of the specimen inside the coil, the calibration, etc.

Tab.5: Errors in the measurements due to the temperature of the equipment and the coil.

T .Equipment [ºC]	Average error [%]	Standard deviation [%]
10	0,565	0,5034
30	0,481	0,5223

The results reveal that in any case neither the average error nor the standard deviation reach 1%. In the quality control of FRC, this error in the measurement may be considered negligible.

3.2 Influence of the temperature of the specimens

In this section, the influence of the temperature of the specimen is analysed by comparing the variations obtained from measuring such specimens at 10ºC, 20ºC and 30ºC with respect to the measurements at 0ºC (see Figure 4). Notice that the temperature of the equipment and the coil is maintained at 20ºC. Analogously to the previous section, the variation in the temperature measurements is presented in terms of the sum of the values in the three directions.

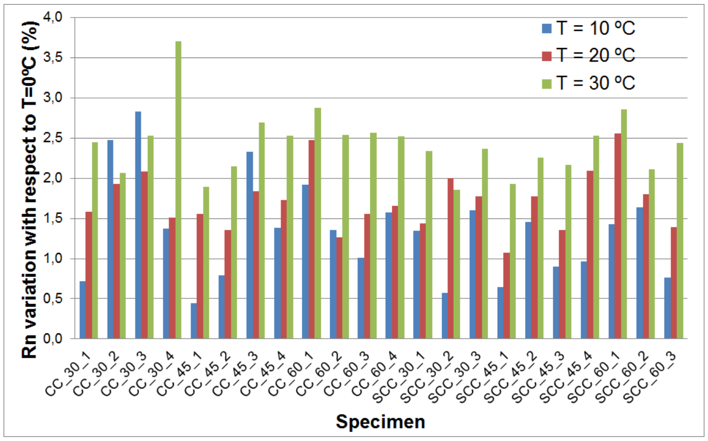

Fig. 4: Variation of the inductance measurements for temperatures of the specimens of 10ºC, 20ºC and 30ºC with respect to 0ºC.

The values in Figure 4 indicate that the variations are significantly higher than that observed in the previous section. In addition, a clear tendency may be observed in this case since the variations are larger for higher temperatures. With the aim of determining whether this tendency needs to be considered in the use of the inductive method, the increment in the measurement for each grade Celsius is calculated according to Equation 2. The measurements in the three axes (X, Y and Z) are considered separately, for each specimen at 0ºC and 30ºC. Notice that L_0 is the measurement with the specimen at a temperature of 0ºC and L_{30} with the specimen at 30ºC.

$$\Delta L / {}^{o}C = \frac{L_{30} - L_0}{30} \qquad (2)$$

Given that the reference measurement was conducted with the specimen at 20ºC, it is necessary to determine if the increment (according to Equation 2) is large or small compared to the reference measurement. For that, the error (in terms of percentage) is calculated for every grade Celsius (see Equation 3).

$$Error(\% / {}^{o}C) = \frac{\Delta L / {}^{o}C}{L_{20}} \cdot 100 = \frac{10}{3} \cdot \frac{L_{30} - L_0}{L_{20}} \qquad (3)$$

The values of the increment of the inductance per grade Celsius and the error per grade Celsius are presented in Table 6.

Tab.6: Average increment and errors in the measurements due to the temperature of the specimens.

Variable	Average	Standard deviation

ΔL/ºC	0,024	0,0131
Erro (%/ºC)	0,077	0,0191

The results in Table 4 indicate that the average error in the measurement is smaller than 0.1%. In addition, the variability of the error is very small since the standard deviation is lower than 25.0%. In other words, the error in the inductance measurement for the range of temperatures 10-30ºC is smaller than 1.0%. This would imply that in a standard dosage of fibres such as 60 kg/m^3 the maximum error would be 0.6 kg/m^3, which may be considered as negligible if compared with the typical error of the method under constant conditions (estimated in 1.5% approximately). Therefore, there is no need to apply any correction to the measurements due to the temperature of the specimens.

3.3 Influence of the temperature of all the elements (equipment, coil and specimens)

The previous sections showed that the errors of each element (equipment, coil and specimens) considered separately may be considered as negligible. Nevertheless, it is possible that these errors are magnified when considered all together. For that reason, the analysis of all the errors together is essential.

Figure 5 presents the results of the variation of the temperature with respect to the reference temperature. In this case, the measurements were taken for temperatures of 10ºC, 20ºC and 30ºC, being 10ºC the reference temperature.

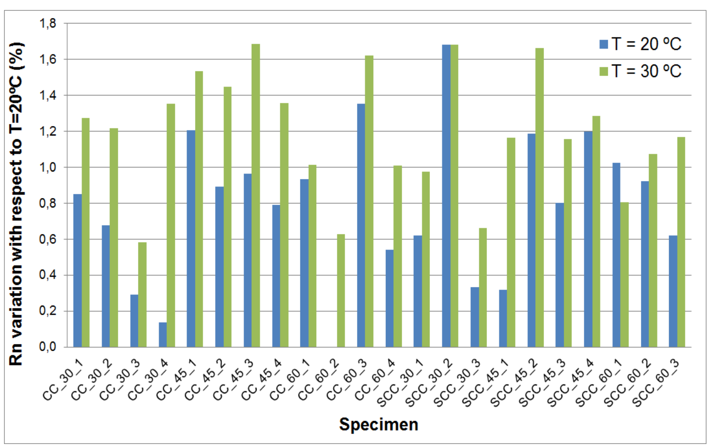

Fig. 5: Variation of the inductance measurements for temperatures of the equipment, the coil and the specimens at the same temparature

The values in Figure 5 reveal a clear tendency of increasing variations with increasing temperature. From this, it is derived that the temperature of the equipment, coil and specimens affects the results. Analogously to the previous sections, the magnitude of the error is subsequently analysed.

Firstly, the increment of the measurement per grade Celsius *ΔL/ºC* is calculated considering separately the measurements in the three axes (X, Y and Z) according to

Equation 4. The measurements were taken at temperatures of 10ºC and 30ºC and compared with the reference temperature (20ºC).

$$\Delta L/^{o}C = \frac{L_{30} - L_{10}}{20} \quad (4)$$

These increments do not have a special meaning for the analysis of the error since their importance depends on the magnitude of the measurements. For this reason, it is more useful to express the errors in terms of percentage, considering 20ºC as a reference. This way the measurements are assumed to be exact and the error per grade Celsius is defined by the expression in Equation 5. Notice that L_{20} represents the measurements with the equipment, the coil and the specimens at 20ºC. The results are summarized in Table 7.

$$Error(\%/^{o}C) = \frac{\Delta L/^{o}C}{L_{20}} \cdot 100 = \frac{10}{2} \cdot \frac{L_{30} - L_{10}}{L_{20}} \quad (5)$$

Tab.7: Errors in the measurements due to the temperature of the specimens.

Variable	Average	Standard deviation
ΔL/ºC	0.0193	0.0119
Erro (%/ºC)	0.0653	0.0352

The results in Table 7 reveal that the average error in the inductance measurement per grade Celsius is smaller than 0.1%. The standard deviations are slightly larger than that obtained in the analysis of the influence of the temperature of the specimens. Despite that fact, their values are still small to be considered in the inductance measurements.

4. Conclusions

In the present study, the influence of the temperature of the equipment, the coil and the specimens in the inductance measurements of the inductive method was analysed by considering 8 different combinations of temperatures. The results show that the temperature of the specimen is the parameter that has the biggest influence on the inductance measured. On the contrary, no clear influence was observed regarding the temperature of the equipment.

In any case, the analysis reveals that the effect of the temperature is negligible if compared with the typical error of the method. This conclusion is of great significance and confirms the robustness of the test. Based on the study conducted, it may be stated that the results of the inductive method may be directly obtained and no additional calibration depending on the temperature is required for the equipment used in the experimental program.

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