Inductive method for the orientation of steel fibers in recycled mortars

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H I G H L I G H T S

- It's possible the complete substitution of natural by recycled aggregates in mortars.
 - Addition of orientated fibers improves the mechanical properties of cement mortars.
 - A magnetic system has been developed to orientate steel fibers in cement mortars.
 - It's possible to qualify magnetically the quantity of fibers orientates in mortars.
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A B S T R A C T

Mortars elaborated with recycled aggregates raise two main difficulties: lower mechanical strengths and higher shrinkage compared to traditional mortars. For this reason, fibers were used to improve the properties. Steel fibers are the most employed for their ferromagnetic qualities, what helps to orient them influenced by magnetic field. This paper argues how recycled mortars with steel fiber oriented under the influence of 500 mT field reach flexural strengths 10% higher than those with non-oriented fibers. Thus, mechanical strengths are closer to traditional mortars. Inclusion of fibers in mortar is suitable for obtaining shrinkage values similar to those obtained in traditional mortars.

1. Introduction

Within the construction sector, the aging of buildings is problematic. Therefore, further studies that enable enhancing the properties of building materials are needed. This will allow their use in the refurbishing and restoration of buildings. In Spain, almost 2% of buildings are in a dilapidated condition and 7.6% are in poor condition. That means that there are more than 963,300 buildings that should undertake works of integral restoration [1,2].

Apart from that, the massive exploitation of natural resources in the construction sector has grown steadily in the last decades. This fact has facilitated the development of new environmental policies that intend to favor the use of new materials with a lower environmental impact [3]. In this context, the construction and demolition waste (CDW) produced throughout the life-cycle of the building is growing in strength as a possible alternative to the use of the traditional building materials. The recycled aggregates (RA) are being

one of the most employed components in the construction of new buildings [4,5].

The cement mortars remain the most employed binder when executing works in the masonry factories that are built nowadays [6]. It is for this reason that research has been undertaken by replacing totally or partially the natural aggregate, traditionally employed, with another kind of RA. Despite the fact that these recycled aggregates contain impurities such as ceramic materials or gypsum whose content depends on the shredding process, they have provided good results in building applications [7,8]. When referring to aggregates and according to the current EHE-08 [9], the use of recycled concrete aggregate is regulated and limited to the 20% of replacement by natural aggregates (NA). In the case of masonry mortars, there is no limit of replacement. On the other hand, the majority of these studies has been performed on laboratory samples. However, it is true that some authors studies the influence of the size of the sample, opening new ways of investigation and reconsidering the suitability of the tests [10].

One of the main drawbacks of mortars elaborated with RA is that, on the one hand, they have a higher capacity to absorb mixing water and, on the other, they have lower densities than traditional

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mortars [11]. This higher absorption has a direct impact on the initial dosage and this, in turn, has a negative influence as the final mechanical strengths of the mortar lessen. This is due to the higher porosity of these materials [12]. Furthermore, the loss of volume is also more evident comparing to traditional mortars. This is why the recycled mortars show larger shrinkage [13] due to two different things. On the one hand, it can be caused by temperature due to exothermic reaction produced in the hydration of the anhydrous compounds of the cement [14]. On the other hand, it can also be caused by the drying produced when free water that remains stored in capillary pores evaporates due to low levels of relative environmental humidity [15].

Some authors have tried to improve mortars tenacity by incorporating fibers of small length and section in their matrix [16]. These fibers can have diverse origins: carbon, glass, basalt, etc. [17,18], and their inclusion aims to better the mechanical properties of mortars without fiber [19]. The strength to crack propagation increases and the capacity to absorb energy and deformation capacity also improve [20]. Moreover, the harmful effects produced by shrinkage can be also reduced through the control of curing temperatures and the employment of fibers during mixing [21].

Research has been made in order to know the main causes of fibers orientation within the mortar matrix [22]: flow, vibration, type of mortar, casting method, fresh-state properties and formwork geometry. This way of fiber orientation can be conducted by vibration of specimens which will enable to reach orientation percentages close to 60%. This will ameliorate the strength in the specimen in transversal direction to the applied stress [23]. In order to carry out this study, steel fiber has been incorporated because of its ferromagnetic materials. It will let us know the percentage of fibers oriented in all three spatial directions through inductive sensors [24]. Furthermore, a magnetic field generated by a powerful solenoid will be used. Thanks to this, fibers might be aligned in the direction of the coil axis so they will coincide with the longitudinal direction of the specimen. This will improve their flexural strength [25]. Some authors performed multidirectional double perforation tests (MDPT) in concrete samples in order to estimate the efficiency in fibres orientation, the method that presents a great scientific interest for developing concrete structures on the real scale [26].

The objective of this study is to design a system that is capable of orienting steel fibers in a fresh mortar with the aim of improving the mechanical properties of recycled mortars. In order to do that, a system able to generate a magnetic field in the longitudinal direction of the specimen has been implemented. It will also enable to orient fibers so that they will be parallel to the direction of the applied stress which will increase the final strength. Subsequently, thanks to an inductive detection system, it will be possible to quantify the fibers oriented in the chosen direction and to study the improvement of this orientation in the flexural strength and in the shrinkage of mortars specimens. The kind of RA chosen for this study comes from recycled concrete waste due to two different aspects; first, their higher strength in comparison with the ceramic and mixed aggregate; second, it tries to reach lower water absorption.

2. Materials and methodology

2.1. Materials and dosages

In order to elaborate mortar specimens, the following materials have been used: cement, natural aggregate, recycled concrete aggregate, steel fibers, water and additive.

2.1.1. Cement

The cement that has been used is CEM II B/L – 32,5 N because it is the most employed in masonry. The Spanish and European regulation UNE-EN 197-1: 2011 [27] and the instruction for the receipt of cements RC-08 [28] specify properties of this kind of cements. Their main characteristics and chemical composition are shown in Table 1.

2.1.2. Aggregates

Specimens have been elaborated with natural aggregates (NA). The recycled concrete sands have been provided by the Construction and Demolition Wastes Treatment Plant TEC-REC. Due to the worse properties presented by the fine fraction in RA, samples collected were sieved in the laboratory in order to eliminate the remained fine fraction. The RA size has been 0/4 mm (material passing through the 4 mm sieve and retained in the 0.063 mm sieve). Fig. 1 plots the size distribution curve of recycled concrete aggregate.

2.1.3. Steel fibers

In order to elaborate reinforced mortars, smooth steel fibers with reduced thickness have been used. The aim of using them is to achieve a homogeneous and isotropic distribution after having oriented them. It will also enable to improve mechanical properties and shrinkage in recycled mortars. The quantity of fibers in each mix was calculated according to the volume of the aggregate (0.5% and 1%). Table 2 summarizes the main characteristics of these fibers.

Fig. 1. Size distribution curve of aggregates.

Table 1
Characteristics of CEM II B/L – 32,5N.

Physical Characteristics											
Density (g/cm ³)	Specific area (g/cm ²)	Initial set (min)	Final set (min)								
3.02	4000	175	275								
Chemical composition											
Al ₂ O ₃	CaO	Fe ₂ O ₃	K ₂ O	MgO	SiO ₂	TiO ₂	MnO	P ₂ O ₅	Na ₂ O	Loss on ignition	
3.25	60.10	2.56	0.26	1.75	18.13	0.14	0.02	0.16	0.22	11.85	

Table 2
Fibers characteristics.

Fiber type	Length (mm)	Diameter (mm)	Elasticity module (GPa)	Tensile Strength (MPa)	Density (g/cm ³)
Steel	22	0.5	200	1100	7.8

2.1.4. Water

Water employed is innocuous, that is, it does not contain any agent in high quantities so that it could alter final properties of the mortar. To that end, the mixing water has been obtained directly from the tap, safe water of the Community of Madrid according to the requirements of the EHE-08. Table 3 displays the characteristics provided by the Canal de Isabel II.

2.1.5. Mortar mixes elaboration

The mortars that contain recycled concrete aggregate have been elaborated using superplasticizer additive Glenium Sky 604 by BASF company as recommended by its technical department to improve RA mortars consistency. This additive is a high range water reducer and superplasticizer based on polycarboxylate.

On the other hand, the description of the mortars used in these tests has the following coding:

$$N - D - SF - \% \quad (1)$$

where *N* indicates aggregate type, that could be NA for natural aggregate and RA for recycled concrete aggregate, *D* shows relation between cement and sand by weight proportion, letter *X* describes relation between components 1:3 and letter *Y* describes relation between components 1:4, *SF* refers to steel fiber and % shows the fiber percentage added to the mortar mix according to Table 4.

The preparation of all mixes has been developed using the same technique and equipment, following the standard UNE-EN 196-1 [29]. Specimens elaborated with recycled concrete aggregate were prepared using 1% of additive over the weight of the cement, complying with the limits established by the manufacturer. Final dosage can be seen in Table 4. Water content of these specimens was experimentally set in order to achieve mixing with a consistency similar to the plastic one (175 ± 10 mm), according to the standard UNE-EN 1015-2:1998 [30].

2.2. Foundations of magnetism in steel fibers

As it has been explained, the orientation of fibers in mortars can be considered a desired phenomenon as long as the piece works in only one direction. This means that steel fibers work in the mortar matrix strengthening substantially the piece. In order to orient a

big amount of fibers, it is necessary to work with flowable or fluid consistency mortars. In this way, metallic fibers will be oriented under the effect of a magnetic field of a consistent and sufficiently high level.

For this reason, applying magnetic fields in shorter lengths is needed. Big coils are built although they have as disadvantage the need of high voltages and high manufacturing costs. In order to avoid these disadvantages, it could be used a coil designed for the specimen dimensions. To do so, the Biot-Savart law that relates the generation of a resultant magnetic field with a current distribution is applied. Thus, the field created by a current can be expressed differentially with the following Eq. (1):

$$d\vec{B} = \frac{\mu_0}{4\pi} \cdot \frac{Id\vec{l} \times \vec{r}}{r^2} \quad (1)$$

where μ_0 is the magnetic permeability, *I* is the intensity of the current, *s* the distance from the load to the observation point in the field and *B* is the created magnetic field.

The following equations could be obtained by integrating the equation for a finite straight wire as the one presented in Fig. 2 [31]:

$$H_x = 0 \quad (2)$$

$$H_y = -\frac{zI}{4\pi} \cdot \int_b^a \frac{dx}{\left[\sqrt{(x-x_0)^2 + (y-a)^2 + z^2}\right]^3} = -\frac{zI}{4\pi} \left[\frac{1}{(a-y)^2 + z^2} \right] \times \left[\frac{b-x}{\sqrt{(b-x)^2 + (a-y)^2 + z^2}} + \frac{b+x}{\sqrt{(b+x)^2 + (a-y)^2 + z^2}} \right] \quad (3)$$

$$H_z = \frac{(y-a)I}{4\pi} \cdot \int_b^a \frac{dx}{\left[\sqrt{(x-x_0)^2 + (y-a)^2 + z^2}\right]^3} = -\frac{(a-y)I}{4\pi} \left[\frac{1}{(a-y)^2 + z^2} \right] \times \left[\frac{b-x}{\sqrt{(b-x)^2 + (a-y)^2 + z^2}} + \frac{b+x}{\sqrt{(b+x)^2 + (a-y)^2 + z^2}} \right] \quad (4)$$

Table 3
Analysis of water employed for mixing.

Color (mg/l)	pH	Turbidity (UNF)	Conductivity (μS/cm)	Nitrate (mg/l)	Free chlorine (mg/l)	Chloride (mg/l)	Sulfide (mg/l)	Total Hardness (°F)
<1,0	7,9	0,1	108,6	0,6	0,5	3,7	5,3	4,8

Table 4
Dosages in mortar mixes elaboration.

Mix type	Cement/Aggregate ratio	Cement (g)	Aggregate (g)	Water (g)	Steel fiber (%)
NA	1:3	450	1350	247.5	–
	1:4	337.5	1350	209.3	–
RA ⁽¹⁾	1:3	450	1350	306	–
	1:4	337.5	1350	300.4	–
RA-SF-0.5%(1)	1:3	450	1350	306	0.5
	1:4	337.5	1350	300.4	0.5
RA-SF-1%(1)	1:3	450	1350	306	1
	1:4	337.5	1350	300.4	1

⁽¹⁾ All specimens elaborated with recycled aggregates contain 1% of additive over the weight of cement.

Fig. 2. Finite straight wire.

where (x, y, z) are the Cartesian coordinates of the point where the magnetic field is calculated. From this equation, it can be obtained a magnetic field generated by a current with any geometry, just by adding the contribution of all corresponding turns.

In order to ensure that the theoretical calculation is adequate, several solenoids have been implemented. The conclusion reached is that in order to obtain a uniform magnetic field with dispersion lower than 1%, it is necessary to build it with a length superior to the desired uniform region. The coil must not have a number of turns by constant length as the number of turns will be increased at the ends. Thus, a coil is made with 20 cm length and 8800 turns. The magnetic field obtained has been quite uniform, 12,5 cm in the main part of the coil.

As it can be seen in Fig. 3, the size distribution curve correlates well with the curve obtained theoretically. In this way and since the mortar should have just been mixed and it will be still fresh, the ferromagnetic fibers could be oriented in the direction of the solenoid axis by applying a magnetic field in specimens.

2.3. Equipment implemented for the fibers orientation in mortars

As shown in Fig. 4, in order to generate a magnetic field capable of orienting steel fibers in mortars, an electric circuit has been implemented. This circuit has enabled to quantify the intensity of the generated field, with the help of a Teslameter.

The magnetic field is accomplished through a primary coil fed by a function generator and a signal amplifier. In this way, the generated magnetic field inside the solenoid will be proportional to the intensity circulating through it. This intensity might be better measured through the fall of potential produced when passing by

Fig. 3. Adjustment between the theoretical magnetic field and the one obtained experimentally with the implemented coil.

Fig. 4. Equipment diagram for the generation and quantification of the magnetic field.

a 1 Ω pattern resistance connected in series with the primary circuit.

As has been argued above, the magnetic field generated by the solenoid is a maximum in the coil center and it gets reduced as it approaches the ends. This effect is beneficial for the metallic fibers orientation in mortars as this orientation will be higher in the bottom area of the central part in the specimen. This part is under much strength when the flexural test is tested (Fig. 5). This is one of the less successful mechanical characteristics in recycled mortars and it is intended to be improved with the inclusion of fibers.

The flexural strength σ_f is represented by the ratio between the bending moment (M_f) and the moment resisting (W), according to the equation

$$\sigma_f = \frac{M_f}{W} = \frac{\frac{P \cdot l}{4}}{\frac{a \cdot b^2}{6}} = \frac{3 \cdot P \cdot l}{4 \cdot a \cdot b^2} \quad (5)$$

where P is the applied load, l is the distance between two supports, a is the width of the specimen and b is the tip of the specimen.

2.4. Content quantification and fibers orientation

Due to the mortar consistency in liquid form and due to the limitation of the field intensity (around 450 mT), it is not possible to orient all the fibers introduced in the mortar matrix. In order to obtain the amount of oriented steel fibers, the inductive method has been used [32]. A coil, shown in Fig. 6 and with 30 cm length, 8 cm diameter and 1567 turns, has been built. The characteristic parameter of this coil is the coefficient of self-induction as it only depends on geometrical factors such as length, diameter and the thickness of the turns' layers.

In this way, the method of measurement has been gaged measuring the variation of the coefficient of self-induction with the amount of fibers included in the solenoid. The coefficient of self-induction has been measured with the self-induction measuring device MZ-505 and the impedance analyzer Agilent 4395A to 120 Hz. Taking into account that the mortar is a non-magnetic material, the only variation of the coefficient of self-induction would be due to the amount of steel fibers introduced. In Fig. 7, it can be observed that the variation of the coefficient of self-induction is linear with the fibers content.

The verification of the actual content in fibers and the calibration of the inductive method for the type of fiber employed has been done hammering the specimens and measuring the weight of fibers according to the standards UNE-EN 14721:2006 + A1:2008 [33].

2.5. Experimental study

The experimental program has been divided in three well-differentiated phases according to the tests conducted and the classification of the findings achieved.

Fig. 5. (a) Diagram of metallic fiber oriented in the mortar specimen; (b) Flexural strength test according to the standards UNE-EN 1015-11.

Fig. 6. Coil to quantify the orientation and quantity of fibers by an inductive method.

Fig. 7. Correlation between fibers content and the self-induction measured with the solenoid.

In the first phase, the main characteristics of recycled concrete aggregates were studied. In order to do that, a physicochemical characterization of them was carried out through the most representative tests proposed by the standard UNE which regulates the characterization of aggregates for masonry mortars. Subsequently, the study was completed with X-ray fluorescence and X-ray diffraction methods.

In a second phase, recycled and reference mortars were elaborated. Steel fibers were included during mixing and were oriented with a solenoid designed for that particular purpose. The mortar was hardened and cured in the curing chamber for 28 days under 95% humidity and 20 °C temperature. After that, the content of fibers was quantified as well as their orientation inside the specimens mixed with 0.5% steel fiber weight and with 1% steel fiber weight.

Finally, mechanical testing has been conducted in order to know better the characteristics of the elaborated material. In order

to do that, standardized specimens RILEM with dimensions $40 \times 40 \times 160$ mm have been used. After being cured in a humid chamber, their bulk and real density as well as their compacity were studied. Subsequently, flexural and compressive tests were conducted following the guidelines of the standard UNE-EN 1015-11:1999 [34] which regulates flexural and compressive tests on mortars.

In addition, shrinkage measuring was also carried out with a manual comparator that measured the variation in the specimens lengths during each drying phase, since they have been unmoulded following the standard UNE 80-112-89 [35], and measuring in specimens with dimensions $25 \times 25 \times 287$ mm. Therefore, shrinkage is expressed as a percentage $\Delta L_{nd}(\%)$ respect to the initial length given by the following Eq. (6):

$$\Delta L_{nd} = \frac{M_{nd} - M_{1d}}{L_0} 100 [\%]. \quad (6)$$

where L_0 is the inner length of the mould, M_{nd} is the comparator measure after n days and M_{1d} is the comparator measure on the first day.

The shrinkage measurement period was 180 days since the specimen had been removed from its mould till the last measurement. These measures enable to quantify the beneficial effect of the inclusion of fibers in the matrix of the recycled mortars and also to study the feasibility of the fibers orientation with the aim of improving their strengths and their final shrinkage.

3. Results and discussion

3.1. Recycled concrete aggregates characterization

Recycled concrete aggregates characterization was accomplished following the standard UNE-EN 13139:2002 [36]. The results of physical and chemical characteristics for both recycled concrete aggregates (RCA) and natural aggregates (NA) are listed in Table 5 [37–40].

As it can be seen in Table 5, the density of recycled concrete aggregate (RCA) is lower than the natural aggregate (NA) density whereas water absorption values of the RA are much higher than the values obtained by NA (as set out in the consulted literature). This high water absorption is the main reason to have recycled mortars with a higher shrinkage. However, the values of absorption reached are below the recommended for this kind of materials [41].

The obtained results of X-ray fluorescence method for the recycled concrete aggregate are shown in Table 6.

Results in Table 6 indicate that, for RA, there is a high level of silicates SiO_2 (68.2%), followed by a high percentage of Al_2O_3 and CaO. Besides that, SO_3 content (0.338%) does not exceed the limit

Table 5
Characterization of the aggregates.

Test	Fine Content (%)	Particle Form	Fineness modulus (%)	Friability (%)	Bulk. dens. (Kg/m ³)	Dry dens. (Kg/m ³)	Water Absortion (%)
Standard	UNE EN 933-1	UNE-EN 13139	UNE-EN 13139	UNE-EN 83115	UNE-EN 1097-3	UNE-EN 1097-6	UNE-EN 1097-6
RCA	3.97	Not relevant	4.28	24.12	1310	2100	6.01
NA	2.58	–	4.25	22.63	1560	2450	0.95

Table 6
X-ray fluorescence.

Aggr.	Al ₂ O ₃	CaO	Fe ₂ O ₃	K ₂ O	MgO	SiO ₂	MnO	TiO ₂	SO ₃	P ₂ O ₅	Na ₂ O	l.Loss (%)
RCA	6.98	10.67	1.22	2.16	0.54	68.2	0.022	0.15	0.338	0.1	0.22	9.4

of 1% established by the standard UNE-EN 13139:2002 for the aggregates used in mortar fabrication as higher levels of this chemical damage the mechanical characteristics of the elaborated mortars reducing significantly their durability.

The crystalline structures and the purity of specimens were analyzed by X-ray diffraction (XDR). The X-ray diffraction pattern was measured using a Cu-K α radiation ($\lambda = 1.540598 \text{ \AA}$) by a diffractometer equipped with a monochromator of graphite. Data were collected at 300 K in steps of 0.05° measured in a range of $10^\circ \leq 2\theta \leq 110^\circ$ taken every 10 s with a current of 20 mA and a 40 kV voltage.

As it can be seen in Table 7, the main crystalline phases obtained with the X-ray diffraction method are quartz and calcite. The number of stars is used to quantify the relative abundance of each crystalline phase in analysed samples.

3.2. Orientation and fibers distribution

Firstly, the fibers orientation inside the specimens of fresh mortars was performed. Fig. 8 shows the actual image of the implemented equipment in order to generate the magnetic field capable of causing the desired effect. The molds used for the specimens RILEM $4 \times 4 \times 16 \text{ cm}$ were designed in wood with the aim of having a non-ferromagnetic material. The magnetic field generated for fibers orientation was close to 500 mT, value experimentally tested that enables to orient a large number of fibers in the surface of the specimen and less in the center itself, as it is here where the

mortar weight and the consistency of the pastry undermine this task.

Complementary tests were carried out in order to verify the correct orientation of fibres in the concrete matrix. Firstly, as shown in Fig. 9, a cuts were made in the sample in order to visualize the distribution of the fibres inside the samples and to check if indeed wanted distribution was carried out. In particular, in Fig. 9(b) shows homogenous distribution of metal fibres in all the transversal section of mortar, that corresponds to the central cut. On the other hand, Fig. 9(c) shows fibres orientation in longitudinal direction of the sample that corresponds to the direction of application of magnetic field created by the solenoid in order to improve mechanical properties of the material.

On the other hand, microscopy test through backscattered electrons was carried out as shown in Fig. 10. No cracks of big size were observed in the mortar matrix, only in some areas corresponding to recycled aggregates, so a good cohesion aggregate/cement can be assessed in this kind of mortars. In particular, Fig. 10(a) shows formation of ettringite needles what is characteristic for conglomerates made with cement due to the reaction of tricalcium aluminate with setting regulator [X]. Moreover, in samples elaborated with recycled aggregates, intergranular fracture is observed, in other words the material breaks at the edges of rounded grains. Fig. 10(b) shows the orientation of metal fibres inside mortar matrix improving mechanical properties of the material. All the fibres present the same orientation and are perfectly adhered to the binder.

In order to gage the inductive method and know both, fibers content and orientation, 100% of fiber content introduced during mixing in specimens within the solenoid was oriented. This enables to quantify the induction as shown in Fig. 11. The introduced fibers content was previously weighed based on the mixing percentages used to elaborate the specimens with recycled concrete aggregate.

Thus, measuring the differences in the coefficient of self-induction, a relation between this variable and the amount of

Table 7
X-ray diffraction analysis.

Material	Mineral relative abundance			
	Calcite	Phologotipe	Quartz	Sandine
RA-Concrete	****	*	*****	**

Fig. 8. Equipment designed to orient fibers in the mortar ma.

(a)

(b)

(c)

Fig. 9. (a) Oriented sample with cuts; (b) Transversal section with homogeneous distribution of steel fibres; (c) Longitudinal section with oriented steel fibres.

(a)

(b)

Fig. 10. (a) Ettringite crystals formed in the binder with 80 µm definition; (b) Metal fibres oriented and adhered to mortar matrix with 2 mm definition.

oriented fibers can be obtained. As it can be observed in Fig. 11, when fibers are oriented in the longitudinal direction of the specimen parallel to the solenoid axis, the variation of the coefficient of self-induction increases with respect to the random fibers orientation. However, when they are oriented in transversal direction, this variation decreases, whatever their orientation is axis Y or axis Z.

Once the induction produced by fibers orientation in the three directions of the space was known, it was possible to identify the percentage of oriented fibers within the mortar matrix by measuring this answer in the induction. The results of the orientation percentages for each type of mixing are displayed in Fig. 12.

As reported in Fig. 12, the solenoid designed as a method to orient fibers in the mortar matrix is validated. In both specimens elaborated with 0,5% and 1% of steel fiber, the prevailing orientation direction is the longitudinal that corresponds to the solenoid axis and to the direction in which the magnetic generated field is more intense. This let us orient fibers in transversal direction to the most unfavorable stress, that in this study, it is the flexural test.

3.3. Mechanical tests

Before mechanical tests, a characterization of mortars was carried out. It was analyzed their bulk density, their real density and

Fig. 11. 100% Fibers orientation. (a) Random, (b) Longitudinal, (c) Transversal Z.

Fig. 12. Induction variation according to the direction of the oriented fibers within the specimen.

compacity due to their relationship in the mechanical behavior of the material (Table 8).

As Table 8 shows, the compacity and density of the mortars elaborated with NA is considerably higher to those elaborated with recycled concrete aggregate. This fact has an impact on the lower mechanical properties of the last mentioned mortars. The inclusion

of steel fibers in percentages 0.5% and 1% does not increase significantly any of these properties.

Besides that, in Table 9, it can be seen how the inclusion of fibers increases substantially the flexural strength in the recycled mortars (with differences between the specimens with inclusion of oriented fibers and those without orientation). In dosage with

Table 8

Bulk density, real density and compacity of the mortars used in this study.

Test (without fibers)	M – NA		M – RA	
	1:3	1:4	1:3	1:4
Bulk Density (g/cm ³)	2,06	1,98	1,74	1,71
Real Density (g/cm ³)	2,32	2,27	2,22	2,27
Compacity (%)	88,79	87,22	78,38	75,33
Test (with fibers)	M – RA – SF – 0,5%		M – RA – SF – 1%	
	1:3	1:4	1:3	1:4
Bulk Density (g/cm ³)	1,75	1,72	1,77	1,72
Real Density (g/cm ³)	2,25	2,28	2,26	2,29
Compacity (%)	77,09	75,43	78,31	75,10

Table 9

Flexural and compressive strengths.

Test (without fibers)	M – NA		M – RA	
	1:3	1:4	1:3	1:4
Flexural Strength (MPa)	5,12	3,87	4,02	2,84
Compressive Strength (MPa)	21,94	14,75	14,23	9,22
Test (with fibers)	M – RA – SF – 0,5%		M – RA – SF – 1%	
	1:3	1:4	1:3	1:4
Flexural Strength (MPa)	4,25	2,94	4,45	3,03
Compressive Strength (MPa)	14,34	9,29	14,71	9,78

inclusion 1% in oriented steel fiber, the flexural strength increases around 17% in dosage 1:3 whereas in dosage 1:4 it is around 14%. On the contrary, the compressive strength also improves although it is not significant as it does not exceed 6%.

3.4. Shrinkage

Shrinkage is one of the main disadvantages of the RA mortars as they require higher amount of water for mixing elaboration due to

Fig. 13. Percentage of oriented fibers in the three directions of the space within each specimen.

Fig. 14. Shrinkage test, dosage: 1:3.

Fig. 15. Shrinkage test, dosage: 1:4.

their higher absorption. This can cause dimensional changes in the material. For this reason, the measurement period was 180 days and it could be observed that the adverse effect produced by this characteristic can be reduced with the inclusion of oriented steel fibers through the inductive method proposed in this study. Figs. 13 y 14, corresponding to 1:3 and 1:4 dosage, respectively.

As it can be seen in Figs. 14 and 15, the inclusion of steel fibers oriented in the RA mortars practically equals their shrinkage to the one provided by NA mortars. Shrinkage is reduced in a 38% in those specimens elaborated with 1:3 dosage and 1% of oriented steel fiber. Shrinkage will be reduced in a 28% in those specimens elaborated with 1:4 dosage in recycled concrete aggregate and 1% inclusion of steel fiber.

4. Conclusions

From the characterization of the recycled aggregate employed to mixing, some differences in comparison with NA were observed, that is, lower density and higher absorption. The recycled concrete aggregates provided by the company TEC-REC are mainly composed by silicates and show quartz and calcite are the main crystalline phases. Furthermore, their size distribution curve as well as the rest of their properties meet the requirements to be used as aggregates for the masonry mortar manufacturing.

Apart from this, it has been designed a solenoid capable of orienting the metallic fibers in the recycled mortars in order to improve their mechanical and shrinkage properties. The implemented equipment is able to generate a magnetic field of 500 mT that has enabled the orientation of around 60% of fibers in the correct direction. It has also been designed a coil capable of verifying the orientation percentages in the three directions of the space. Thus, the implementation of the inductive method in this kind of materials is validated.

In relation to the properties of recycled mortars, the inclusion of steel fibers ameliorates both their mechanical strengths and shrinkage. These properties are usually penalized due to the characteristics of the RA. Results in mechanical testing show that fibers orientation in recycled mortars increases the flexural strength in around 10% with respect to the non-oriented mixing. However, the compressive strength does not show a significant improvement

due to the orientation that does not correspond with the direction to the applied stress. Finally, the results obtained in the shrinkage study show how inclusion of steel fibers in 1% enables to reach similar values to those obtained in the traditional mortars at 178 days (0.49 mm/m for dosage 1:3 and 0.593 mm/m for dosage 1:4) reducing possible cracks and increasing the durability of this material.

Declaration of Competing Interest

None.

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