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Experimental evaluation of cement mortars with recycled brass fibres from the electrical discharge machining process

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HIGHLIGHTS

- Recycled brass fibres from electrical discharge machining were used in mortars.
- Mortars with machined fibres were similar to those with not-machined fibres.
- Fibres did not alter mortar consistency but increased its thermal conductivity.
- Fibres were too short to improve mechanical properties of the mortar.

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ABSTRACT

This paper aims to evaluate the effect of recycled brass fibres on the physical, thermal and mechanical properties of cementitious mortars. For that purpose, seven different mortars, with the same water/cement ratio but using two different brass fibres were manufactured. Not-machined brass fibres were used as a reference and compared to the waste brass fibres obtained as a by-product of wire cutting methods through electrical discharge machines. Both fibres were added to the mortars in proportions of 0.25%, 0.5% and 1% by volume of mortar. The morphology and presence of elements in the fibres were evaluated by scanning electron microscopy (SEM) coupled with energy dispersive X-ray spectroscopy (EDX). In addition, ultrasonic pulse velocity and thermal conductivity were measured to evaluate the mortar quality and the fibre dispersion into the mortar specimens. Mechanical properties were studied through flexural and compression tests. Since the fibres present a reduced length, the effect on both porosity and bulk density is negligible and the reduction on ultrasonic pulse velocity and compression strength and the slight increment on flexural strength is not remarkable due to the limited anchorage provided. Nonetheless, the improvement in the thermal conductivity of the developed mortars with recycled brass fibres, supports focusing on the niche market of heating installations, such as underfloor heating or closed-loop geothermal heat exchangers.

1. Introduction

As result of the exponential global population growth, the demand on the construction industry is also continuously growing. With the aim of decreasing the cost, energy consumption and use of raw materials on the construction industry, waste valorisation of old buildings for new uses has gained interest. Cement mortars are composite materials widely used in civil engineering either to repair structures or to be a part of the building envelope system due to its physical, mechanical and thermal properties [1]. For that purpose, different types of fibres are currently used to enhance the specific physical and mechanical properties required to mortars on each case [2,3]. In particular, natural fibres [4], carbon fibres [5], synthetic fibres [6,7], and metallic fibres [8–10] are commonly used to modify the mortar fresh and hardened properties.

Synthetic fibres are usually added as a primary reinforcement on thin composites and as a secondary reinforcement to improve the mortar durability by reducing the crack generation due to shrinkage during its hardening process [2]. Carbon and steel fibres are added with the same goals as for the synthetic fibres, but also to increase the adherence capacity of the reinforced mortar, which enables its use to repair structural elements [5,11]. However, due to the high cost of commercial carbon fibres, most of the structural repair mortars use either polypropylene or steel fibres as an economic alternative for repairing mortars. No matter the type of fibre

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used as a reinforcement, commercially available mortars use specifically designed fibres, which involves a high-energy consumption associated to its manufacturing process. To reduce both the energy required during this process and the landfill disposal of industrial waste, the reuse of different metallic scraps has been proposed as a reinforcing material by different authors, such as carbon or steel fibres [5,8,11,12], granulated steel particles [13], steel shavings or even steel wool fibres [14,15]. Among those studies, mechanical properties are the most analysed properties, being the thermal ones, less assessed.

Regarding physical and mechanical properties of cementitious materials reinforced with fibres, Norambuena-Contreras and coworkers [5,14,15] studied the effect of adding recycled fibres such as carbon micro-fibres, steel wool and steel shavings, on the physical and mechanical properties of Portland cement pastes and hardened mortars at different ages of curing. Authors concluded that the addition of fibres decreased the bulk density, increased the porosity and had an insignificant effect on the mechanical properties of the resulting cement composites. Martinelly et al. [12] used recycled steel fibres recovered from end-of-life tires as a partial-to-total replacement of the usually used industrial steel fibres. They concluded that concretes reinforced with recycled steel fibres had similar flexural and compressive strengths to that of the concretes reinforced with industrial steel fibres. Although post-cracking behaviour was negatively affected, it was still significantly better than that of the non-reinforced concrete. Moreover, Quadir et al. [13] added recycled granulated steel particles as a partial replacement of natural fine aggregate on concretes, which increased the workability of the mix, its flexural strength and its compressive strength.

With respect to the thermal properties, Nagy et al. [16] evaluated the influence of different fibre types in concrete, remarking that steel fibre reinforced concretes had higher bulk density and thermal conductivity values than concrete reinforced with synthetic fibres, which was attributed to the higher thermal conductivity and density of the former fibres. Girardi et al. [17] added steel fibres, powder and recycled shavings to concrete to evaluate their influence on the thermal properties of the concrete for its potential use as a thermal-energy storage material. According to their results, the thermal conductivity of the concrete increased by 97%, 116% and 169% due to the addition of steel fibres, particles and shavings, respectively. Nevertheless, other studies indicate that the increase in thermal conductivity caused by the steel particle addition is usually smaller [11,18]. For instance, authors as Khaliq et al. [18] used 1.75% by volume of self-consolidating concrete with, either or both, steel fibres and polypropylene fibres, concluding that the steel fibres increased the thermal conductivity and the polypropylene fibres reduced it.

In short, fibre-reinforced cementitious materials is a hot-topic with great progress in recent years. Nonetheless, there is few scientific papers regarding the use of brass fibres as reinforcement on cement composites, even less for the use of fibres obtained as a by-product from the electrical discharge machining process. This paper aims to evaluate the influence of adding short brass fibres on the physical, thermal and mechanical properties of cement mortars. To do that, seven different mortars, with the same water/cement ratio, but with two different brass fibres types, and three different percentages have been evaluated.

2. Materials and methods

2.1. Raw materials

Mortars were made with the same proportions of water (w), cement (c), superplasticizer (sp) and limestone sand (s). The main difference between the seven mixed mortars was the fibre type and proportion of fibres used for each mixture: while the reference (R) mortar was made without any reinforcement, two different brass fibres were used in three different proportions by unit volume of mortar: 0.25%, 0.5% and 1%. Furthermore, not machined brass fibres (B) were obtained by using the electrical discharge machine only to cut the original continuous brass wire. Therefore, there was no chemical change or material loss during the cutting process. Since recycled brass fibres (B*) were obtained during the normal functioning of the Electrical Discharge Machine (EDM), final geometry and material properties of the recycled fibres would vary depending on the use of the EDM, which is initially random and unknown.

CEM II-B (L)/32.5R type cement was chosen in agreement with EN 197-1. This cement is a mix of Portland cement and up to 35% of limestone filler by weight, valid for the use in foundation concretes and masonry mortars in general. Its compressive strength is greater than 13.5 and 42.5 MPa at an age of 2 and 28 days, respectively. Grain-size distribution of the limestone aggregate used by weight was determined according to EN 933-1, which is shown in Table 1. Apparent particle density (ρ_l) and water absorption were also obtained according to EN 1097-6. CHRYSO 550 superplasticizer admixture was used as water reducer for obtaining a nearly self-consolidating reference mortar.

Additionally, both types of fibres were mechanically cut by the waste disposal system of the EDM, but only the recycled brass fibres were exposed to the degrading action of the machining process. With the aim of determining their geometrical characteristics, not machined and recycled brass fibres were randomly taken from the existing stock. A calliper and a micrometre were used to determine the length and diameter of up to 200 fibres for each fibre type. Fig. 1(a) and (b) shows the appearance, geometry, length and diameter of both not machined and recycled brass fibres, respectively.

From Fig. 1, it can be observed that not machined brass fibres had a diameter of 0.25 mm, and an almost constant length of 10 mm, which was the predefined length for the cutting system included on the EDM machine. For the recycled brass fibres, a nearly constant diameter of 0.22 mm was determined, while the fibre length varied from 6 to 11 mm as some fibres broke before reaching the cutting system of the EDM machine. Regarding the density, it was considered that both brass fibres had a similar density, 8400 kg/m^3. As can be seen in Fig. 1(b), the damage caused by the machining process on the recycled brass fibres is evident. As the rugosity of the machined fibres was remarkably higher than that of the not machined fibres, X-Ray Diffraction (XRD) and energy dispersive X-Ray fluorescence (ED-XRF) tests were carried out by PANalytical Xpert PRO Diffractometer and FISCHERSCOPE X-Ray equipment to determine possible changes on their elemental composition. Results showed that not machined brass fibres were composed approximately of 63.7% of Cu and 35.3% Zn, as it was expected. In recycled brass fibres, despite the changes observed on microscope, those proportions kept similar one with respect to the former, but slightly lower in total due to the appearance of up to 1% of Fe in some points of the samples tested. Additionally, morphology of both fibres was analysed with a JEOL JSM-6400 Scanning Electron Microscope (SEM), see image results in Fig. 2.

As for the results obtained on XRD and ED-XRF tests (Fig. 3), mainly elements as Zn and Cu were observed on all the spectrums evaluated. In this case, there is a presence of oxygen, which would indicate that the surface was slightly corroded, but the quantity was not significant. However, EDX results also detected the presence of Mo, Fe, Ni and Cr in some areas, which made sense as the EDM is mainly used to machine components made by inconel or steel. Overall, their quantities were not significant and were not uniformly dispersed on the fibres.

2.2. Test specimen preparation

Cement mortars consisted on cement, water, superplasticizer and three different fibre proportions by mortar volume: 0.25%, 0.5% and 1%. Table 2 shows the mix proportions used in this study. In order to obtain a reference mortar with a normal consistency, water to cement ratio of 0.5 by weight was set to all the mortar mixtures according to EN 196-3:2005 + A1:2009. Thus, all the mortars had the same water:cement:limestone-sand:superplasticizer proportions by weight, 0.5:1:3:0.01. Therefore, the only difference between the mortars was the fibre type and quantity to be used in the mix, which would change the proportions of the other compounds used per cubic metre of mortar, but not the weight proportion ratios between them.

For each mortar, six 40 × 40 × 160 mm^3 prismatic test specimens were prepared in compliance with EN 1015-10. Mixing process was similar for all the batches. Firstly, dry cement and limestone sand were mixed for one minute at low speed. After that, water and superplasticizer were added and mixed for another minute at the same speed. Then, mortar was mixed for one minute at high speed to interrupt the mixing process for 2 additional minutes. To finish with the reference mortar mixing process, the mixture was again mixed at high speed for another minute.

For the mortars with brass fibres, fibres were gradually added to the already mixed mortar with the mixer working at low speed for another 2 min. After finishing the mixing process, resulting fresh mortar was poured to the centre of each prismatic mould to provide a more homogeneous fibre distribution inside the specimens. Then, moulds were vibrated at a frequency of 300 Hz for 10 s for obtaining a homogeneous consistency in all the mixes. For 24 h after making the mix, test specimens were sealed and cured under ambient laboratory conditions and then, specimens were submerged in water at 20 °C until 28 days curing age was reached.

Table 1
Grain-size distribution of the limestone aggregate.

Sieve size [mm]	4	2	1.18	0.6	0.4	0.2	0.1	0.063
% Pass	100	92	68	44	35	22	15	13

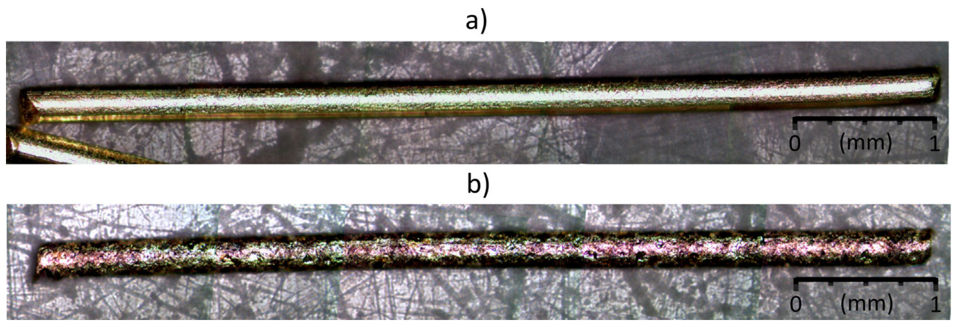

Fig. 1. Appearance of the brass fibres studied: (a) not machined, and (b) recycled.

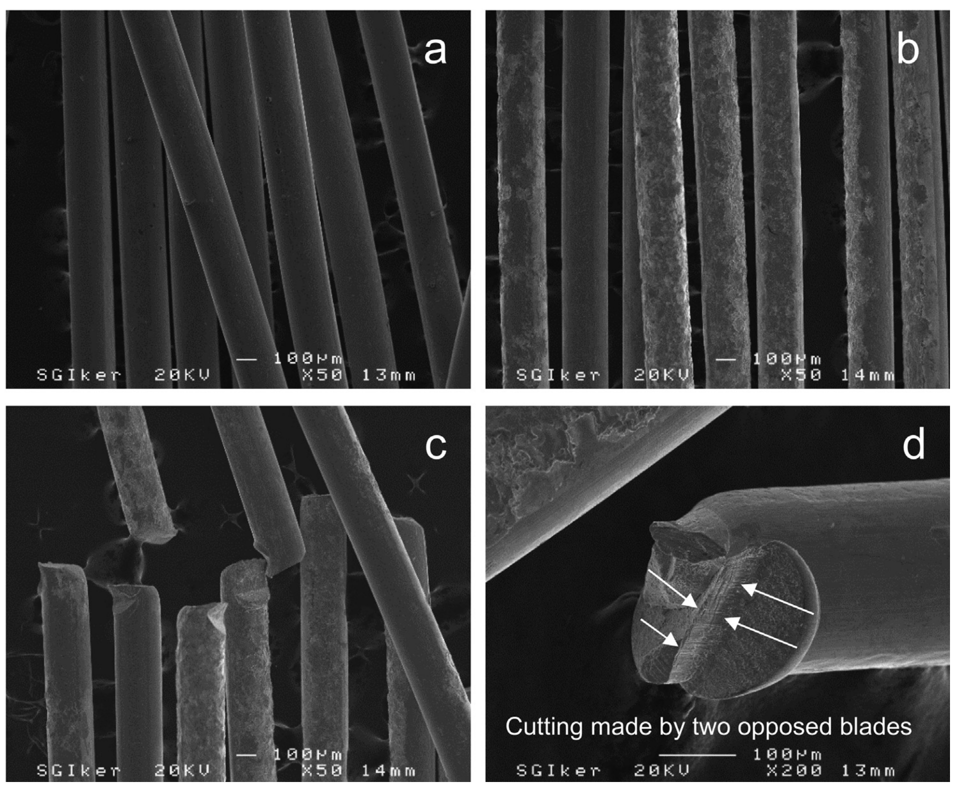

Fig. 2. Appearance of the fibres studied by SEM: (a) general view of not machined brass fibres; (b) general view of recycled brass fibres; (c) appearance of the ends of both fibres; and (d) detail of a representative end of both fibre types.

2.3. Consistency of the fresh mortar

To determine the influence of the fibre addition on the workability of the resulting mortar, consistency of the fresh mortar was determined by the flow table consistency test according to EN 1015-3. Thus, consistency of all the mortars was similar and close to the 220 mm set for the reference mortar.

2.4. Bulk density and porosity of the mortar test specimens

To determine the influence of the brass fibre type and content on the physical properties of the mortars after 28 days, dry bulk density (ρ) and water accessible porosity (n) where measured on each specimen by Eqs. (1) and (2) according to the standard EN 1015-10. The representative values for each mortar type was determined as the average value of 6 specimens.

$$\rho = \frac{m_{dry}}{m_{sat} - m_w} \cdot \rho_w \tag{1}$$

$$n = \frac{m_{sat} - m_{dry}}{m_{sat} - m_w} \tag{2}$$

where m_{sat} is the water-saturated mass of the prismatic specimens; m_w is the water-submerged mass of the test specimens; m_{dry} is the oven dried mass of the test specimens and ρ_w is the water density at testing temperature.

2.5. Ultrasonic pulse velocity of the mortar test specimens

Ultrasonic pulse velocity (UPV) was measured on each mortar after 28 days with two different goals: first, to estimate the fibre distribution inside each specimen and also, to determine its capability of detecting the quality of the mortars with the fibre presence. Ultrasonic direct tests were carried out by using a Proceq Pundit PL200 ultrasonic velocity tester. The used test procedure was based on the method published by Norambuena-Contreras et al. [14]. Two 150 kHz piezoelectric

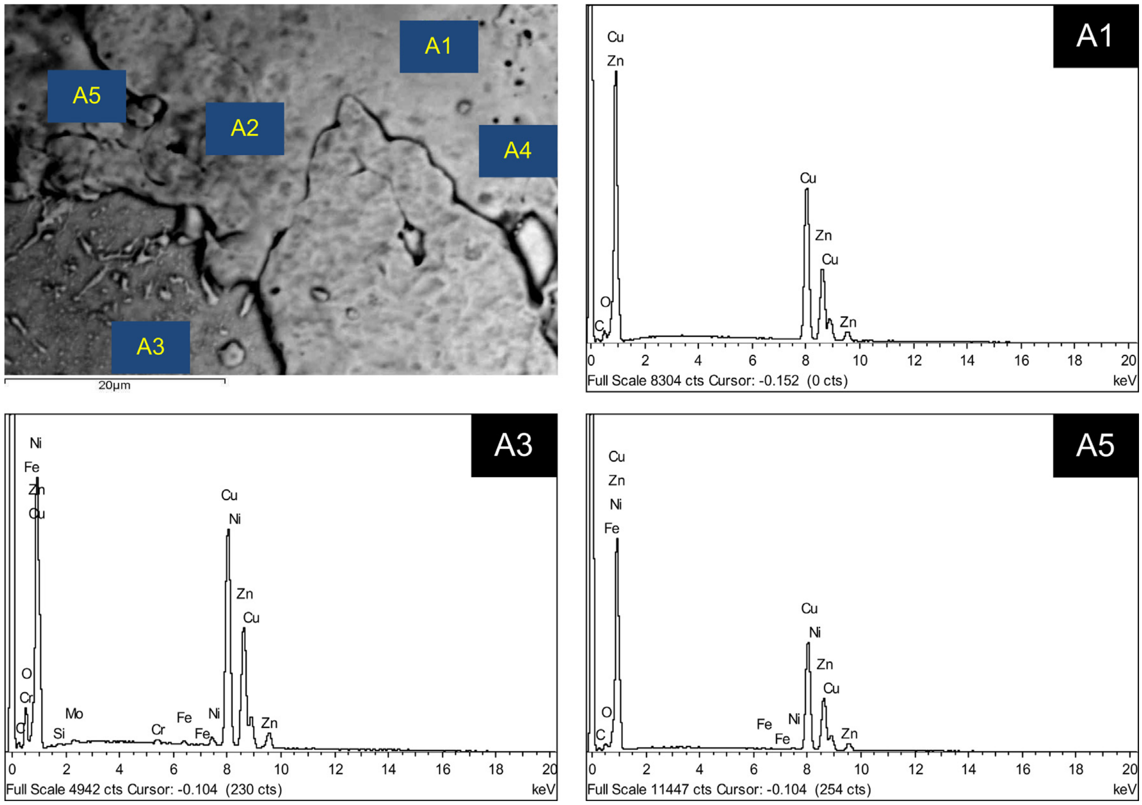

Fig. 3. SEM/EDX spectrum results obtained on surface of recycled brass fibres.

Table 2
Mix proportions used in this study.

Mix ID	Cement (kg/m^3)	Limestone sand (kg/m^3)	Fibre type (–)	Fibre (kg/m^3)	Superplasticizer (l/m^3)	Water (l/m^3)
R	527	1582	None	0	5.2	264
0.25B	525	1574	Not machined Brass Fibres (B)	22.5	5.2	262
0.5B	522	1566		45	5.2	261
1B	517	1550		90	5.2	258
0.25B*	525	1574	Recycled	22.5	5.2	262
0.5B*	522	1566	Fibres	45	5.2	261
1B*	517	1550	(B*)	90	5.2	258

transmitters were used to evaluate the mortar behaviour. To guarantee a good contact of the transducers with the tested specimens, petroleum jelly was used on all the tests.

Five different tests were carried out on each specimen: one in the longitudinal direction of the specimen to evaluate the mortar overall quality, and four more measurements on each quarter along the transversal direction of the specimen to determine the homogeneity of each specimen. Taking into account that the pulse must go through a length (L) of 160 mm and 40 mm for the longitudinal and transversal tests, the ultrasonic pulse velocity (V) was determined from the time (t) the pulse needed to go from the emitter to the receiver, according to Eq. (3):

$$V[\mathrm{m/s}] = \frac{L[\mathrm{m}]}{t[\mu s] \cdot 10^{-6}} \tag{3}$$

Based on Norambuena-Contreras et al. [14] results, in this study higher ultrasonic pulse velocities would be caused by a higher fibre concentration, as the pulse velocity is approximately double on brass than that of most of the concretes. However, lower pulse velocities would be attributed to the higher porosity of the test specimen in that zone. Finally, the representative value of the propagation time on each point was calculated as the average of three different measurements made on the same positions and test conditions, respectively.

2.6. Thermal conductivity and thermal diffusivity of the mortar test specimens

The thermal conductivity (λ) and thermal diffusivity (α) were determined to quantify the influence of the fibre content on the thermal properties of the resulting mortars. The thermal conductivity of the hardened mortar was determined for each test specimen based on the Transient Plane Source (TPS) method developed by Gustafsson [19]. This method has been successfully used to determine thermal properties of highly porous building materials, insulation building materials, hydrating cement pastes and even mortars containing waste metallic fibres and shavings [11,20–22].

Fig. 4 shows the setting of the tests carried out with a HotDisk M1 thermal conductivity tester. Two 40 × 40 × 160 mm^3 prismatic test specimens were used in each test to make a sandwich surrounding the Kapton 8563 sensor. The test consisted of heating a 19.8 mm diameter disk at a constant P_0 heating rate and measuring the temperature increment of the disk itself for an initially undetermined time. According to Gustafsson [19], the time-dependent $\Delta T(\tau)$ sensor temperature increase is (4):

$$\Delta T(\tau) = \frac{P_0}{\pi^{\frac{3}{2}} \cdot a \cdot \lambda} \cdot D(\tau) \tag{4}$$

where a is the sensor radius, λ is the mortar thermal conductivity and $D(\tau)$ is a time dependent dimensionless function that depends on the sensor and on the τ dimensionless time (5):

$$\tau = \sqrt{\frac{t \cdot \alpha}{a^2}} \tag{5}$$

where t is the elapsed time since the beginning of the test, and α is the thermal diffusivity of the material. In this manner, the average temperature increment after a relatively short time period only depends on P_0, λ, α and t. According to the TPS theory, the temperature increase is linearly dependent on the $D(\tau)$ function [19]. Therefore, α and λ are obtained via an iterative process by forcing Eq. (4) to be a straight line. After some preliminary tests, heating power and testing time were set to 1.5 W and 40 s, respectively.

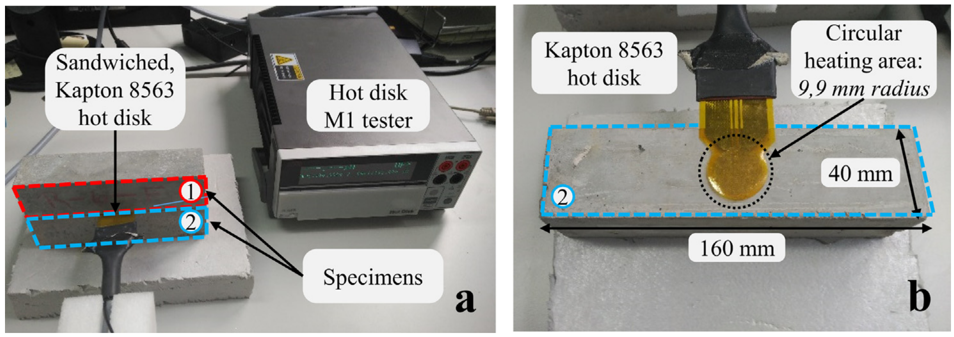

Fig. 4. Thermal conductivity analysis: (a) set-up of the thermal conductivity tests carried out; and (b) detailed dimensions and positioning of the sensor used.

Thermal conductivity and thermal diffusivity of the hardened mortars were evaluated at an age of 28 days. As the tests were performed on the test specimens used to determine both density and porosity of the material, specimens were kept sealed at 25 °C in the laboratory for 2 days in order to cool down and reach thermal equilibrium. Conductivity and diffusivity were calculated as the average of the 3 tests carried out on each of the 3 pairs of specimens tested. Finally, the average tests values were also calculated to determine the representative thermal properties.

2.7. Flexural and compressive strengths of the hardened mortars

For the evaluation of the mechanical properties of the hardened mortars, flexural and compressive strengths were determined according to the standard EN 1015-11. The test was displacement-controlled on the flexural strength test to quantify the post-cracking behaviour of the fibre-reinforced mortars. In this case, displacement velocity was set to 0.5 mm/min. Otherwise, compressive test was load controlled, with a load increment ratio of 0.5 kN/s. Test specimens were tested for flexural strength and the resulting halves were subjected to compressive tests. Finally, the average flexural and compressive strength of each studied mortar was determined as the average value of the six specimens and twelve halves tested, respectively.

3. Results and discussion

3.1. Effect of fibres on the density and porosity of the hardened mortars

Dry bulk density and water accessible porosity of the hardened mortars were evaluated, whose results are shown in Fig. 5. According to the dry bulk density, it remains almost constant and there is not any significant influence of neither the fibre type nor the proportion used. Regarding porosity, for the not machined brass fibre reinforced mortars; there is an increase of 5.4% and 5.6% and 4.8% for the 0.25B, 0.5B and 1B mortars, respectively, with respect to that of the reference mortar. For the recycled brass fibre reinforced mortars, that increase was of 8.6%, 6.9% and 4.8% for the 0.25B*, 0.5B* and 1B* mortars, respectively. So, overall the addition of fibres increased the water accessible porosity, which contributed to counteract the density increasing effect the fibres would yield due to their higher density. Hence, it is assumed that the non-accessible porosity increased in a similar way, due to the internal fibre interaction and fibre cluster formation [14] into the specimens.

In any case, the porosity on B* mortars was slightly higher than that of the B mortars, which is attributed to the higher surface roughness of the recycled brass fibres, which eased the formation of fibre clusters and made the fibre to paste contact more difficult.

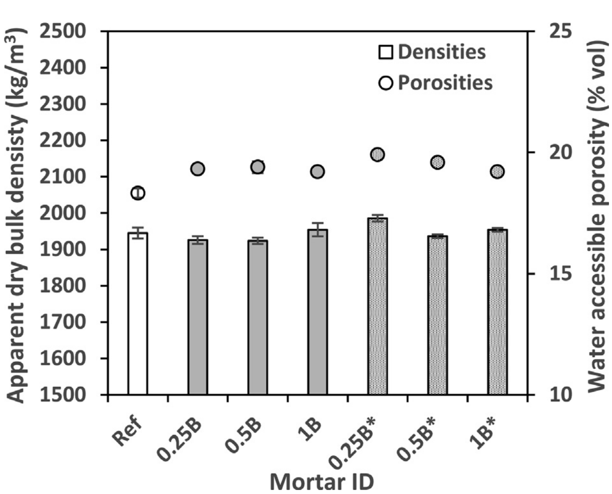

Fig. 5. Effect of the brass fibre type and proportions used on the dry bulk density and porosity of the hardened mortars.

3.2. Recycled brass fibre distribution inside of the hardened mortars

Fig. 6 shows the average ultrasonic pulse velocities obtained in the five positions tested. It was observed that the longitudinal UPV (see Fig. 6(a)) for B mortars decreased by 5.9% and 5.7% and 5.8% for the 0.25B, 0.5B and 1B mortars, respectively, with respect to that of the reference mortar. Similarly, UPV on B* mortars decreased by 5%, 5.4% and 9% for the 0.25B*, 0.5B* and 1B* mortars, respectively. According to the results obtained on the longitudinal direction (see Fig. 6(a)), UPV of the reference mortar was clearly the highest among all the evaluated mortars. At the same time, UPV on mortars containing 1% of recycled fibres was also visibly lower than that of the rest of the mortars tested. Furthermore, the rest of the mortars studied presented similar intermediate values between the maximum and minimum values observed for the R and 1B* mortars, respectively. In any case, as opposed to the water accessible porosity, the fibre presence decreased the UPV. Initially, the fibre should increase the UPV due to the higher transmission velocity of the brass in comparison to that of the raw mortar. However, fibres tended to increase mortar accessible porosity, which reverted this effect.

On the other hand, the average transversal UPV (see Fig. 6(b)) assessed for B mortars showed a decrement of 5%, 5.4% and 6%, compared to the reference mortar, in case of 0.25%, 0.5% and 1% raw fibre addition, respectively. Likewise, UPV on B* mortars decreased by 4.6%, 5.3% and 8.2% for the 0.25B*, 0.5B* and 1B* mortars, respectively. The tendency was similar to that observed for the longitudinal direction. Nevertheless, transversal UPV absolute values were higher than longitudinal ones for all the cases, with a maximum increase of 2.5% for the 0.25B mortar. Near the test specimen walls, the compaction effect reduced the porosity more effectively, which increased the UPV on that area. Since this porosity reduction took place in a similar thickness on the four vertical walls of the specimen, the thickness of the improved area with respect to the total length the pulse must go through was higher

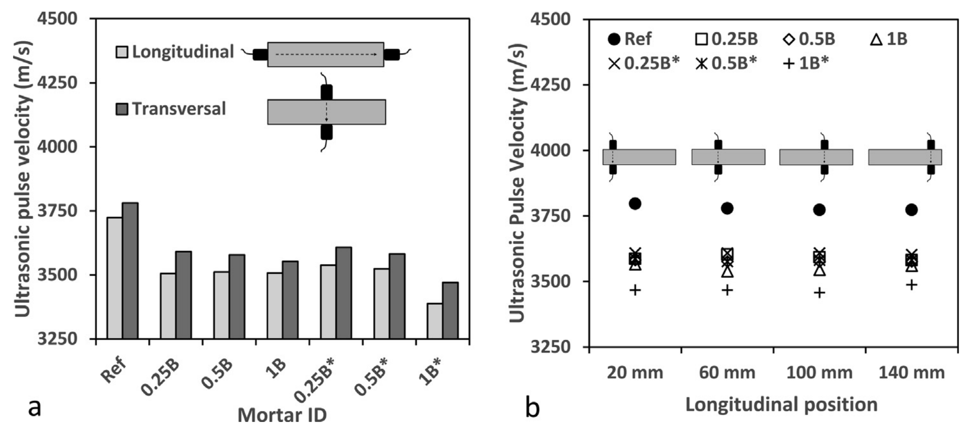

Fig. 6. Effect of the brass type and proportion used on the ultrasonic pulse velocity of the mortars: (a) longitudinal and transversal mean values; (b) transversal direction.

for the transversal direction, causing the increase observed on the measured UPV on that direction.

Additionally, as transversal UPV was measured in four equally distanced points, the results shown in Fig. 6(b) could also be used to study the homogeneity of the mortar test specimens. For all the mortars evaluated, results were consistent and constant along all the specimen length, and the difference between specimens of the same mortar and batch, insignificant. Based on UPV results, the authors concluded that the fibre distribution and porosity could be considered uniform on all the specimens tested, regardless of the type of brass fibre (i.e. not machined and recycled) and proportions (0.25%, 0.5% and 1% by mortar volume) used.

3.3. Thermal conductivity and volumetric heat capacity of the hardened mortars

Thermal conductivity results of cement mortars are shown in Fig. 7. Regarding the B fibre reinforced mortars, thermal conductivity was reduced by 1.9% and 1.7% for 0.25B and 0.5B mortars, respectively, taking the non-reinforced mortar as a reference. Nevertheless, for the mortar containing the highest amount of fibres, 1B, an increase of 5.1% was obtained. For the mortars reinforced with B* fibres, thermal conductivity was 8.9%, 0.2% and 4.5% higher than that of the reference mortar for 0.25B*, 0.5B* and 1B* mortars, correspondingly. Regarding the volumetric heat capacity, on B mortars the observed value diminished by 10.3%, 11.2% and 17.7% for 0.25B, 0.5B and 1B mortars, in that order. Similarly, for B* mortars the reduction was of 0.9%, 10.8% and 10.2% for 0.25B*, 0.5B* and 1B* mortars, respectively.

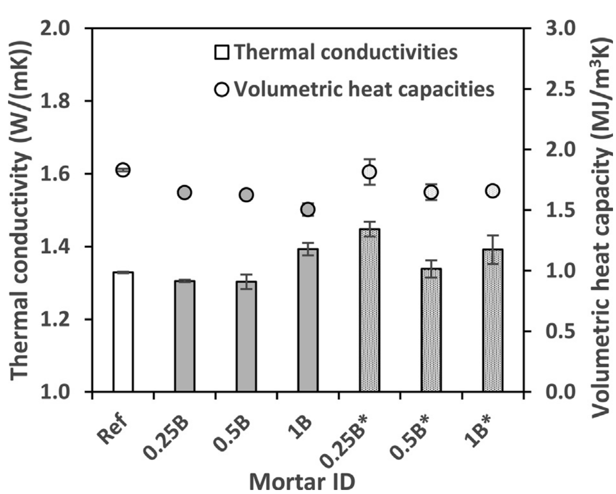

Fig. 7. Effect of the brass type and proportion used on the thermal conductivity and volumetric heat capacity of the hardened mortar.

It is known that the thermal conductivity of the brass (109 W/(m K)) is significantly higher than that of the rest of the mortar components. Consequently, volumetric heat capacity of the brass (3.3 MJ/(m^3 K)) is approximately 50–75% higher than that of most of cement composites. Hence, adding brass fibres should increase both thermal conductivity and volumetric heat capacity. However, different authors have determined that these variations not only depend on the fibre proportions used, but also on the fibre distribution and fibre interconnection [5,11,15].

In this case, the higher amount of water lost due to the higher water accessible porosity of the fibre-reinforced mortars caused a reduction of the volumetric heat capacity that compensated the increase expected due to the fibre addition. Similar conclusion was obtained for the thermal conductivity, as the thermal conductivity of the less reinforced mortars even decreased in some cases, which was attributed to the porosity increase associated to the fibre addition. Furthermore, fibres seem to be too short to ensure a proper interconnection that would lead to higher thermal conductivities than those observed in this research. Nonetheless, the mortars proposed could be an interesting solution to reduce the thermal inertia of heating and cooling installations such as radiant floors or closed-loop geothermal heat exchangers, due to their higher thermal conductivity and lower volumetric heat capacity.

3.4. Influence of brass fibres on the mechanical properties of the hardened mortars

Fig. 8 shows the flexural and compressive strengths of the mortars as a function of the fibre type and proportion used as a reinforcement. For both mortars, no matter the reinforcement used, both compressive and flexural strengths decreased due to the fibre addition.

Regarding flexural strength (see bars in Fig. 8); for B mortars, flexural strength was diminished by 15.9%, 12.4% and 4.6%, for 0.25B, 0.5B and 1B mortars with respect to the reference mortar, respectively. Likewise, flexural strength of B* mortars was 11.3%, 8.8% and 18.9% higher for 0.25B*, 0.5B* and 1B* with respect to that of the non-reinforced mortars, in that order. Thus, adding low fibre proportions of not machined brass fibres tend to weaken the mortar, but as the fibre proportion increased, most of the flexural resistance was recovered. However, for the recycled fibre reinforced mortars, the use of higher fibre proportions led to increasingly higher weakening of the resulting mortar. Similar results were obtained for the compressive strength. For B mortars, flexural

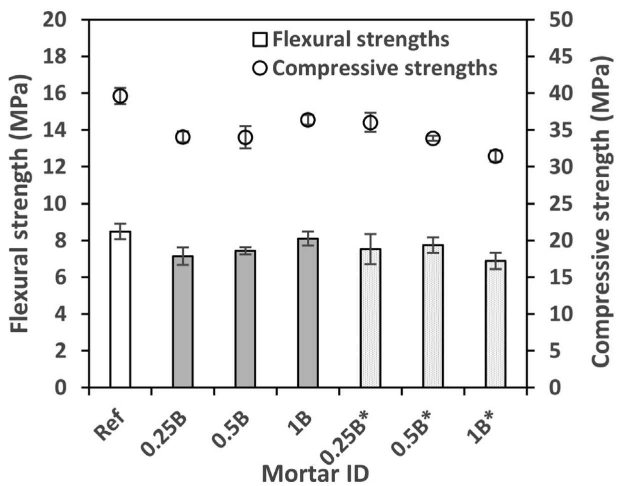

Fig. 8. Influence of the brass type and proportion used on the flexural and compressive strengths of the hardened mortars.

strength was 14%, 14.1% and 8.2% lower for 0.25B, 0.5B and 1B mortars to that of the reference mortar. Accordingly, B* mortars suffered a decrease on flexural strength of 9%, 14.5% and 20.6% for 0.25B*, 0.5B* and 1B* mortars.

For both flexural and compressive strengths, the reduction was generally higher for the recycled brass fibre reinforced mortars. Normally, the expected variation on compressive strength (see points in Fig. 8) is minor or tends to increase with the proportion of fibres used on fibre reinforced cementitious materials [2,9]. Norambuena-Contreras et al. [14,15] observed that the compressive strength slightly descended on mortars reinforced with waste steel wool fibres or steel shavings. As in that case and based on the water accessible porosity and UPV velocity increases observed on waste brass fibre reinforced mortars, the authors consider that it is the porosity increase the main responsible for the decreases observed on both flexural and compressive strengths. Furthermore, post-cracking behaviour of the fibre-reinforced mortar was similar to that of the non-reinforced mortar, which was mainly attributed to the insufficient length of fibres used [2]. To prove that, samples broken by flexural test were observed under an optical microscope. Fig. 9 shows two situations were fibre addition increased mortar porosity.

As it could be seen in Fig. 9(a) and (b), most of the fibres were surrounded by big pores, with diameters of up to 2 mm. As the fibre length was 10 mm for the raw fibres, and 6 to 11 mm for the recycled fibres, the presence of those pores reduced significantly the available cement paste to fibre adherence surface. As a result, fibres were mainly pulled out of the fibre matrix and only few of them broke due to excessive stress (see Fig. 9(a)). For the recycled brass fibres, each pore supposed approximately 18%–33% of the total length of the shortest and the longest fibres, respectively, while for the raw fibres, this percentage was slightly lower, 20%, as fibres were longer in general. Therefore, the lower strengths obtained for the recycled brass fibre reinforced mortars was caused by the shorter average length of the fibres. Therefore, longer fibre samples should also be tested with the aim of determining the influence of the weakening of the fibres caused due to the machining process.

Despite the negative results obtained, it is worth mentioning that the use of brass fibres reduced significantly the thermal inertia of the resulting mortar. This reduction would be interesting for mortars used on non-structural closed loop geothermal heat exchangers or for mortars used on radiant floor heating systems, were the mechanical properties required (20 MPa required according to EN 1264-4:2010) are significantly lower than the values obtained in this case.

4. Conclusions and recommendations

This paper evaluates the influence of using waste brass fibres from the electrical machining process as a reinforcement on cement mortars. It was quantified the influence of using either not machined brass fibres or recycled machined brass fibres as a reinforcement of cement mortars in different proportions. For that purpose, the same reference unreinforced mortar was modified by adding either not machined or recycled fibres in proportions of 0.25%, 0.5% and 1% by volume of mortar. After studying the physical, thermal and mechanical properties of the hardened mortar at an age of 28 days, Authors reached the following conclusions:

- The addition of either not machined or recycled brass fibres increased the mortar water accessible porosity, which is attributed to the air gaps created between the fibres and the cement paste during the fresh flowing and compaction process.
- The highest ultrasonic pulse velocity was measured on the reference mortar. The higher the proportion of fibres used, the lower was the ultrasonic pulse velocity of the resulting mortar, up to a 5.8% and a 9% for the not machined and recycled brass fibres reinforced mortars, respectively.
- Thermal conductivity increased by up to 5.2% and 8.9% with respect to the reference mortar for not machined and recycled brass fibre reinforced mortars, respectively. The increase was limited by the higher porosity introduced by the fibres.

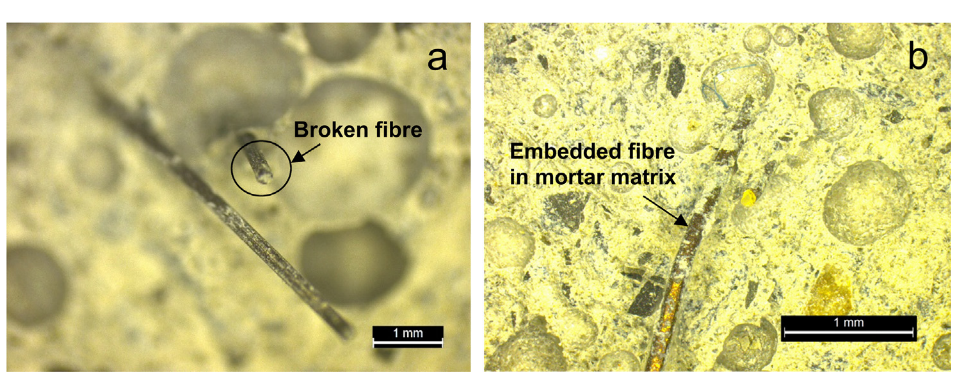

Fig. 9. Effect of the fibres on the porosity and cement paste adherence surface: (a) example of a broken fibre on a sample of raw fibre reinforced mortar, and (b) porosity surrounding the embedded fibres.

- Volumetric heat capacity decreased by up to 17.7% and 10.8% with respect to the reference mortar for not machined and recycled brass fibre reinforced mortars, respectively, as the higher water accessible porosity of the resulting mortars enabled a higher water loss during the mortar drying process.
- Flexural strength was reduced by up to 15.9% and 18.9% with respect to the reference mortar for not machined and recycled brass fibre reinforced mortars, respectively. For compressive strength, results showed the same tendency as for the flexural strength. In any case, this reduction occurred due to the short length of the fibres, combined by the increasing porosity caused by their presence that diminished the fibre to cement paste adherence surface.

This paper presented the results of cement mortars containing recycled brass fibres obtained during the electrical discharge machining process, as it is carried out at the facilities of the Faculty of Engineering of Bilbao at present. Effect of the fibre length would be addressed in a future release by varying the parameters set on the machining equipment during its normal use.

CRediT authorship contribution statement

R. Borinaga-Treviño: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft. **A. Orbe:** Investigation, Visualization, Writing - review & editing. **J. Canales:** Investigation, Writing - review & editing, Funding acquisition. **J. Norambuena-Contreras:** Methodology, Visualization, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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