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Estudio del comportamiento mecánico de morteros de cal hidráulica con y sin fibras de basalto, a diferentes edades.
Study of the mechanical behaviour of hydraulic lime mortars with and without basalt fibres, at different ages.

Analía Vázquez[a]; María Isabel Prieto[a]; María de las Nieves González[a]; Alfonso Cobo[a]

[a] Departamento de Tecnología de la Edificación, Escuela Técnica Superior de Edificación, Universidad Politécnica de Madrid. Avda Juan de Herrrera, 6 28040 Madrid.

Resumen-- **En el trabajo presentado se realiza un estudio acerca del comportamiento de morteros de cal hidráulica con fibras de basalto como material idóneo para emplear en rehabilitación de estructuras históricas por sus buenas propiedades y su compatibilidad con los materiales empleados tradicionalmente en construcción. Tras los estudios anteriores sobre la adición de estas fibras de basalto en diferentes longitudes (6, 12, 18, 24 y 30 mm), se decide repetir los ensayos mecánicos a largas edades (180 días) con la finalidad de confirmar la aptitud de las fibras de basalto como refuerzo de estos morteros de cal hidráulica, que resultan tener un efecto favorable en el comportamiento mecánico tanto a 28 como a 180 días, y para concluir que las fibras de basalto de 12 mm de longitud continúan siendo las que mejor trabajan frente a ensayos mecánicos.**

Palabras clave— Morteros; cal hidráulica; fibras de basalto; compresión; flexión.

Abstract— **In the work presented, a study is carried out on the behaviour of hydraulic lime mortars with basalt fibres as a suitable material for use in the rehabilitation of historic structures due to its good properties and its compatibility with the materials traditionally used in construction. After previous studies on the addition of these basalt fibres in different lengths (6, 12, 18, 24 and 30 mm), it was decided to repeat the mechanical tests at long ages (180 days) in order to confirm the suitability of basalt fibres as reinforcement of these hydraulic lime mortars, which proved to have a favourable effect on the mechanical behaviour both at 28 and 180 days, and to conclude that basalt fibres of 12 mm in length continue to be the ones that work best in mechanical tests.**

Index Terms— Mortars; hydraulic lime; basalt fibres; compression; bending.

I. INTRODUCTION

THERE is a current need for refurbishment of the residential building stock caused by its ageing and by the new energy efficiency standards, which means that most residential buildings do not meet the standards or regulations and intervention is necessary.

According to different studies, the continuous annual growth of the refurbishment business has also been verified, as published by the Ministry of Transport, Mobility and Urban Agenda in its survey on the Structure of Construction. Other results are that since 2012, refurbishment activity in the residential sector has exceeded the volume of new construction business and that between 2017 and 2019 the rate of growth of refurbishment works has increased to a large extent, thus demonstrating the need to refurbish the building stock at a national level (Min. Transportes, 2020; INE, 2020)

In the Royal Decree of 2021 that regulates residential rehabilitation aid or programmes, it is established that 45% of national buildings were built before 1980, and 50% if only residential buildings are studied (Min. Transportes (2021).

Taking these data into account, it is not only important to pay attention to the residential area, but at national level there is a large number of Monuments or heritage buildings that are in a state of ruin and that, as stipulated in the Spanish Heritage Law of 1985, must be intervened, in order to conserve and maintain them (BOE, 1985).

There is also an International Charter on the conservation and restoration of monuments and sites that regulates intervention actions on monuments with the aim of respecting their essence and maintaining their authenticity, always trying to conserve their entire composition (ICOMOS, 1965).

With all these studies, the need to intervene in monuments and the way in which to do it is justified, it must be done correctly and carefully, without damaging the buildings and respecting them in their entirety. To do this, it is necessary to know the most suitable materials for this type of construction, to carry out a study of what materials were used at the time of their construction, and which are compatible with them in order to prevent them from causing any deterioration or accelerating the degradation of the building.

Traditionally, important buildings were built with materials such as lime. Nowadays, lime mortars have been replaced by more modern mortars such as cement mortars or Portland cement. Their use in refurbishment was replaced by the latter because they were slower and more complicated to restore due to their slow setting, because they were less resistant than cement mortars and because of the lack of current studies on their behaviour.

Cement mortars, on the other hand, have higher strengths, faster setting times and a more accessible cost; however, they also have some disadvantages: they are incompatible with many traditional materials and have a very high hardness that other materials do not have (Arandigoyen et al., 2007).

Portland cement is now commonly used in building rehabilitation; however, it has recently been shown to be unsuitable for heritage rehabilitation due to its high incompatibility with traditional building materials such as stone. As with cement mortars, the incompatibilities are mainly due to the fact that the material has a high mechanical strength compared to traditional materials such as stone or brick, and therefore allows less deformation than the base material, leading to the possible appearance of cracks and other pathologies (Silva et al., 2015; Schueremans et al., 2011). It also presents other incompatibilities, such as the presence of salts, which can lead to their migration to the base material and thus accelerate its degradation, or the different coefficients of thermal expansion (Bustos-García et al., 2018).

For these reasons, studies on hydraulic lime mortars as a material for the rehabilitation of historic buildings have increased. Many studies have been carried out on the compatibility of mortars with historic buildings. It is worth noting that a large percentage of these monuments are built of natural stone, hence the article by Stephan Ulrich who studied the compatibility between lime mortars and two types of natural stone from Valencia, the Bateig azul and Barxeta, both of which had different physical properties, but he concluded that the lime mortars presented similar values in terms of flexural and compressive strength to both stones, good compatibility was also obtained in terms of the presence of salts, but as a disadvantage he found a slightly greater durability in the hydraulic lime, a symptom that in case of damage caused by this, it would be concentrated in the stone instead of in the mortar. It is therefore important that the physical and chemical properties of the mortar and the base material are as similar as possible (Kröner et al., 2010).

However, it has also been found that hydraulic lime mortars have certain limitations, such as shrinkage during setting, which if left untreated leads to cracking of the mortar, low ductility and low mechanical strength for structural use. As a solution, there are studies that analyse the incorporation of additives and additions that improve the properties.

The use of reinforcement fibres to improve mechanical properties, mainly basalt, is highlighted as a way of dealing with current problems such as pollution and as a more economical option than other more common ones such as steel, carbon or glass. Basalt is a lightweight, strong, non-combustible, non-toxic, non-oxidisable and more sustainable material, as well as being recyclable through a relatively simple process.

The aim of this research is to determine the behaviour under real conditions of a hydraulic lime mortar reinforced with basalt fibres, justifying any proportion of materials, as well as the conditions set for the study, by means of a review of the literature and previous studies.

After having justified the need for the work and having carried out a previous bibliographical review, the dosages to be used for the mortar are established.

After justifying the need for the work and carrying out a previous bibliographical review, the mortar dosages to be used were established.

To this end, the research carried out by Arturo Bustos is considered, in which he manages to establish the mortar dosage and the most suitable proportion for adding the basalt fibres and obtaining the best properties (Bustos-García et al., 2016).

In addition to considering the aforementioned research by Arturo, the present study is based on that carried out previously by Vázquez Bouzón. In this study, the behaviour of different mortars with the same dosages and reinforced with basalt fibres of different lengths is analysed and compared with a reference mortar, without additions and with the same dosage. For the study, physical and mechanical tests are carried out on the mortar in its fresh and hardened state to determine its properties. As a result of the research, a favourable behaviour of the mortar in the presence of fibres was obtained, and also, that one size of fibres gave a better result than the rest after 28 days of curing of the mortar, those of 12 mm (Vázquez Bouzón, 2021).

II. Methodology

To confirm the results obtained in the research on which the study is based, it was decided to carry out an analysis of the mechanical behaviour at long ages of the same hydraulic lime mortars that were used and thus corroborate the results obtained

TABLE I
DOSAGE OF MORTARS USED FOR PRE-ANALYSES. SOURCE: OWN ELABORATION

	Hidraulic lime	Sand	Water	Fibres	Plasticiser
Initial dosage	1	3	0,73	1% vol.	0,8% lime weight
Initial dosage weight (Kg/m^3)	490	1470	357,7	21,12	3,92
Fibre length (mm)	6, 12, 18, 24 y 30				

and be able to continue with the research.

To this end, mortars are manufactured with the same dosages and with the same reinforcement options with basalt fibres, maintaining the lengths already studied. They are left to cure for a period of 180 days and are tested in flexure and compression.

The curing conditions are maintained, curing is carried out in a humid chamber, but for a period of 180 days. The mortar dosage is also maintained and is detailed in the following table (Table 1).

To designate the specimens, the letters MC for lime mortar are used followed by the length of fibres incorporated or REF in the case of the reference specimen. A total of two flexural specimens and four compression specimens (those resulting from the first test) are tested. The table below shows the designation of the mortars mentioned in Table 2:

TABLE II
DESIGNATION OF MORTARS USED IN THE PREVIOUS ANALYSIS. SOURCE: OWN ELABORATION.

FINAL DOSAGE: lime/limestone: 1/3; water/lime: 0.73; 0.8% plasticiser		
Name	**Fibers (% volume)**	**Fibers Length (mm)**
MC-REF	0	0
MC-6	1	6
MC-12	1	12
MC-18	1	18
MC-24	1	24
MC-30	1	30

The procedure was also the same, the mortar was made by mechanical kneading according to the standard, and the moulds of the test pieces were filled in two batches, passing between them and finally by mechanical compaction with 25 blows. They were placed in a humid chamber and demoulded after 48 hours to ensure the start of setting. They were removed from the humid chamber after 180 days and tested.

Further details of the experimental procedure followed, and the machinery used are given in Table 3.

To manufacture the mortars, the different mortar components were weighed with the help of a precision scale, hydraulic lime, sand, water, plasticiser and fibres in the case of reinforced mortars (Fig. 1 and 2).

The weighed mortar components were mixed with the help of the mechanical mixer (Fig. 3) according to the following process: manually mixing the lime with the fibres on one side and the water with the plasticiser on the other side. The two mixtures were then mixed together and introduced into the mixer, which was programmed according to the UNE-EN 1015-11 standard. Inside the mixer, the mixture was mixed at a slow speed, the sand was added, the mixer was mixed at a fast speed, the container was cleaned and then the mixture was left to rest for a second time, and the final mixing was carried out to obtain the mortar.

Fig. 1. Already weighed mortar components. Source: Photographs by author.

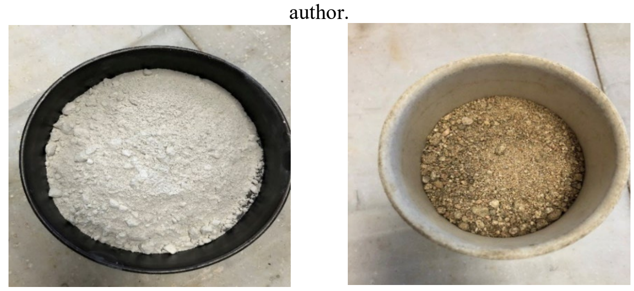

Fig. 2. Already weighed mortar components. Source: Photographs by author.

Fig. 3. IB32-040V01 mechanical mixer from IBERTEST. Source: Photograph by author.

TABLE III
DESIGNATION OF MORTARS USED IN THE PREVIOUS ANALYSIS. SOURCE: OWN ELABORATION.

Process	Equipment	Standard	Characteristics
Kneading	Kneading machine	UNE-EN 1015-11	IB32-040V01 de IBERTEST.
Weighing	Electronic scales		EUROPE 6000 y 3000HR de GIBERTINI
Manufacture	Moulds	UNE-EN 196-1	Moldes de acero templado (40x40x160 mm)
Compaction	Horizontal compactor	UNE-EN 1015-11	CIB-801 de IBERTEST
Curing	Wet chamber	UNE-EN 1015-11	HR ≥ 90 % y T = 20 +- 1 ºC

Fig. 4. Compactadora mecánica modelo CIB-801 de IBERTEST

Fig. 5. Filling and screeding the metal moulds. Source: Photographs by author.

Fig. 6. 180-day flexural test. Source: Photograph by author

Fig. 7. 180-day compressive test. Source: Photograph by author

With the mortar mixture ready, the test specimens were made. For this purpose, the standard prismatic metal moulds were filled in two batches, passing through a process of mechanical compaction by means of 25 blows with the CIB-801 IBERTEST mechanical compactor in accordance with the UNE-EN-1015-11 Standard (Fig. 4).

To fill the moulds manually, a hopper was used (first image in Fig. 5). At the end of the filling process, the hopper was removed, and the moulds were levelled with the help of a spatula to leave the surface of the moulds as smooth as possible (Fig. 5).

At this point, with the specimens made, set and cured for 180 days in a humid chamber, the tests are carried out. In this second investigation, the tests carried out are mechanical bending and compression tests with the aim of assessing the mechanical behaviour of the mortar for use in structures.

The tests were carried out with the help of Ibertest's universal machine model MIB-60/AM, using the respective flexural and compressive adapters in order to analyse the deformations as shown in Fig. 6 and 7:

III. Results

This section presents the results of the tests carried out throughout the experimental phase. All the tests that have been carried out are on the mortar in a hardened state.

Mechanical tests have been carried out. Mechanical tests are those that help to determine the properties that result from applying an external force on the material. In this case, the properties of flexural strength and compressive strength are determined.

In order to differentiate the specimens, different colour codes are used in the graphs that will be followed later in the comparison of results. A table with the colours used in each of the cases is given in (Table 4:

Table IV
Description of colours for specimens tested at 180 days

DESCRIPCIÓN PROBETAS	
ENSAYOS A 180 DÍAS	
MC-REF	Mortero de referencia, sin refuerzo de fibras
MC-6	Mortero reforzado con fibras de 6 mm
MC-12	Mortero reforzado con fibras de 12 mm
MC-18	Mortero reforzado con fibras de 18 mm
MC-24	Mortero reforzado con fibras de 24 mm
MC-30	Mortero reforzado con fibras de 30 mm

A. *Flexural strength after 180 days.*

In the bending tests, a total of 2 specimens are tested for each of the models.

In all cases, the values of maximum force, maximum deflection and maximum bending stress are analysed and detailed in a table in order to determine the most representative specimen, as there are only two specimens, the one that is considered to be the most accurate is taken in the form of a graph.

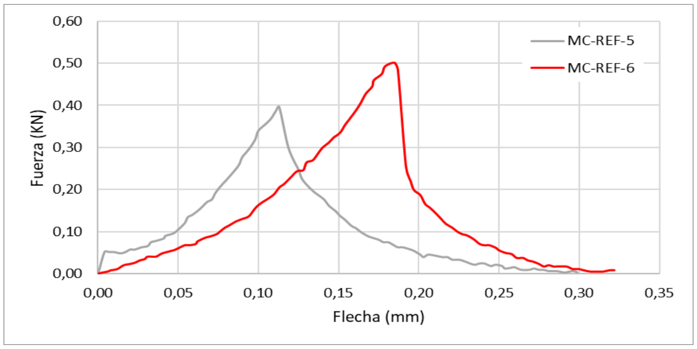

Fig. 8. Flexural graphs of MC-REF specimens at 180 days. Source: Own elaboration

TABLE V
RESULTS OF BENDING TESTS ON MC-REF SPECIMENS AT 180 DAYS. SOURCE: OWN ELABORATION

NOMBRE	$\sigma_{máx}$ (N/mm^2)	$F_{máx}$ (KN)	$\delta_{máx}$ (mm)
MC-REF-5	0,248	0,397	0,113
MC-REF-6	0,313	0,501	0,185
Medias	0,281	0,449	0,149

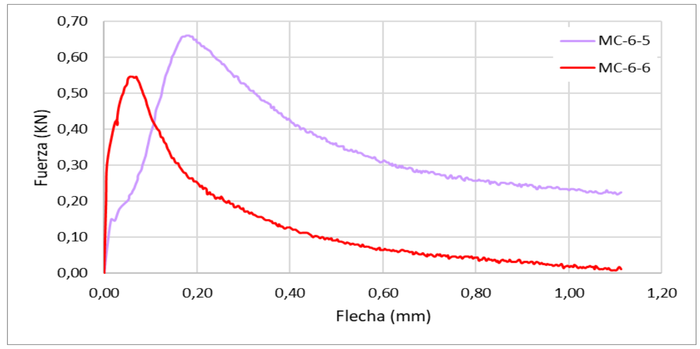

Fig. 9. Flexural graphs of MC-REF specimens at 180 days. Source: Own elaboration

TABLE VI
BENDING TEST RESULTS ON MC-6 TYPE SPECIMENS. SOURCE: OWN ELABORATION

NOMBRE	$\sigma_{máx}$ (N/mm^2)	$F_{máx}$ (KN)	$\delta_{máx}$ (mm)
MC-6-5	0,413	0,661	0,177
MC-6-6	0,341	0,546	0,069
Medias	0,377	0,604	0,123

The graphs of each of the models with the respective tables with the detailed characteristic values are attached below.

In the reference specimens, specimen number 6 shows a more abrupt drop, which is why it is taken as representative, as it does not have fibres in the composition, the breakage is fragile (Fig. 8 and table 5).

In the test specimens with 6 mm fibres, the number 6 is again taken as the characteristic, as it is believed to present the most suitable behaviour according to previous studies. Slightly higher stresses than in the reference specimens and with ductile rupture, but with quite pronounced graphs. The one chosen is marked with red in the graph and purple in the table (Fig. 9 and Table 6).

In the MC-12 specimens, the same thing happens as in the previous ones; number 6 is chosen as the representative specimen because of its behaviour, and because the drop in tension after rupture is smoother than in number 5. During the test, a maximum force of 0.775 KN and a maximum deflection of 0.19 mm are reached (Fig. 10 and Table 7):

In the case of the specimens reinforced with 18 mm fibres and tested at 180 days, specimen number 5 is taken as significant, as it shows a significantly more ductile behaviour than specimen number 6, despite the fact that it reaches lower forces during the test, 0.679 KN compared to 0.93 KN for specimen 5 (Fig. 11 and Table 8).

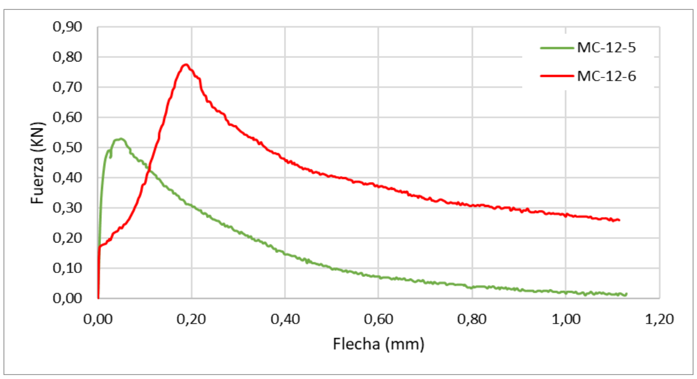

Fig. 10. Flexural graphs of MC-12 specimens at 180 days. Source: Own elaboration

TABLE VII
RESULTS OF BENDING TESTS ON MC-12 SPECIMENS AT 180 DAYS. SOURCE: OWN ELABORATION

NOMBRE	$\sigma_{máx}$ (N/mm^2)	$F_{máx}$ (KN)	$\delta_{máx}$ (mm)
MC-12-5	0,330	0,528	0,05
MC-12-6	0,484	0,775	0,19
Medias	0,407	0,651	0,120

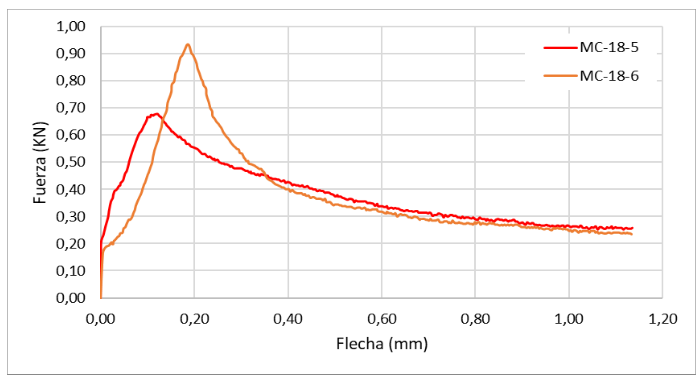

Fig. 11. Flexural graphs of MC-18 specimens at 180 days. Source: Own elaboration

TABLE VIII
BENDING TEST RESULTS ON MC-18 TYPE SPECIMENS. SOURCE: OWN ELABORATION

NOMBRE	$\sigma_{máx}$ (N/mm^2)	$F_{máx}$ (KN)	$\delta_{máx}$ (mm)
MC-18-5	0,425	0,679	0,122
MC-18-6	0,584	0,935	0,187
Medias	0,504	0,807	0,155

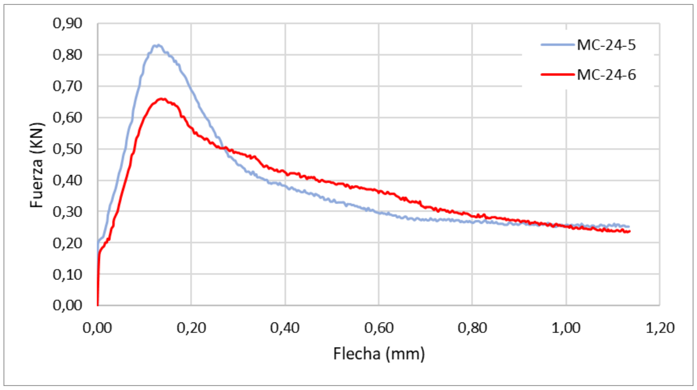

Fig. 12. Flexural graphs of MC-24 specimens at 180 days. Source: Own elaboration

TABLE IX
RESULTS OF BENDING TESTS ON MC-24 SPECIMENS AT 180 DAYS.
SOURCE: OWN ELABORATION

NOMBRE	$\sigma_{máx}$ (N/mm^2)	$F_{máx}$ (KN)	$\delta_{máx}$ (mm)
MC-24-5	0,519	0,831	0,13
MC-24-6	0,411	0,658	0,144
Medias	0,465	0,745	0,137

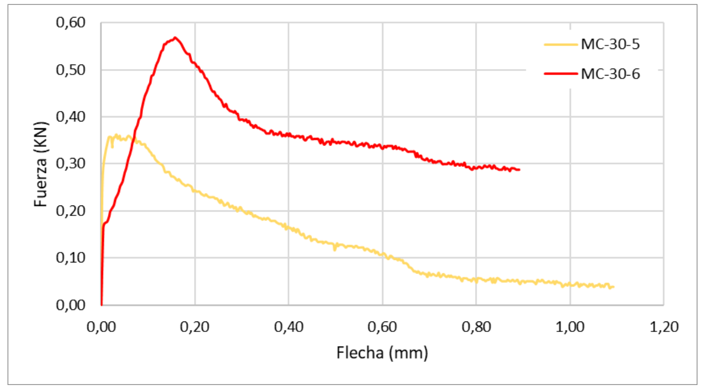

Fig. 13. Flexural graphs of MC-30 specimens at 180 days. Source: Own elaboration

TABLE X
BENDING TEST RESULTS ON MC-30 TYPE SPECIMENS.
SOURCE: OWN ELABORATION

NOMBRE	$\sigma_{máx}$ (N/mm^2)	$F_{máx}$ (KN)	$\delta_{máx}$ (mm)
MC-30-5	0,226	0,362	0,032
MC-30-6	0,356	0,569	0,157
Medias	0,291	0,466	0,095

Finally, for the specimens with fibre lengths of 24 and 30 mm, the number 6 is selected as the characteristic of each of the models. In both cases, graphically, the specimen shows a more ductile behaviour than the other, regardless of the stresses reached. In the MC-24, the one with the lowest stress is selected because, despite the fact that the maximum deflections are similar, it has a graph with a lower drop. For MC-30, the one chosen is the one with the highest tension, the highest resistance and the highest maximum deflection (Fig. 12 and Table 9 for MC-24) (Fig. 13 and Table 10 for MC-30).

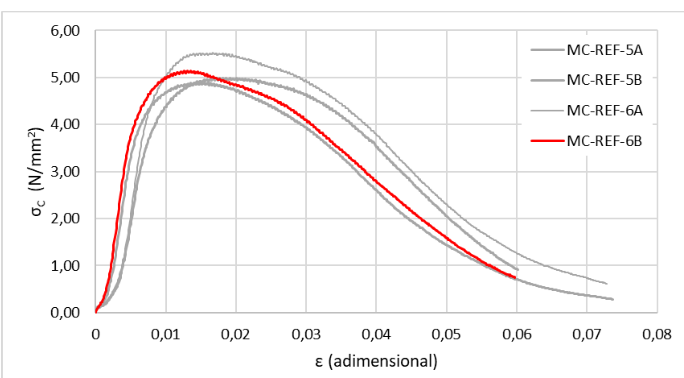

Fig. 14. Compressive graphs of MC-REF specimens. Source: Own elaboration

TABLE XI
RESULTS OF COMPRESSIVE TESTS ON MC-REF SPECIMENS.
SOURCE: OWN ELABORATION

NOMBRE	$\sigma_{máx}$ (N/mm^2)	$\varepsilon_{máx}$ (adim.)	$E_{máx}$ (N/mm^2)	$\sigma_{últ}$ (N/mm^2)	$\varepsilon_{últ}$ (adim.)	$E_{últ}$ (N/mm^2)
MC-REF-5A	4,991	0,020	0,065	0,917	0,100	0,201
MC-REF-5B	4,883	0,015	0,049	0,285	0,100	0,188
MC-REF-6A	5,525	0,017	0,060	0,618	0,073	0,233
MC-REF-6B	5,141	0,013	0,046	0,749	0,060	0,193
Medios	5,135	0,016	0,055	0,642	0,083	0,204

B. *Compressive strength after 180 days.*

In the compression tests, a total of 4 specimens are tested for each of the models obtained from those resulting from the bending tests.

In this case, the values of maximum and ultimate stress, maximum and ultimate unit strain, and maximum and ultimate strain energy density are calculated. This last parameter represents the strain energy density absorbed during the test and is a representative parameter of the ductility of the mortar.

To determine the characteristic specimen for each of the models, attention is again paid to the graphs obtained from the test and to the tables with the properties analysed and their mean values, which are presented below. For the reference

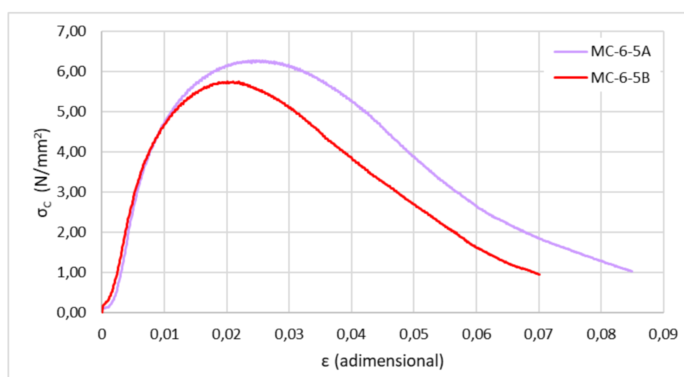

Fig. 15. Compressive graphs of MC-6 specimens. Source: Own elaboration

TABLE XII
RESULTS OF COMPRESSIVE TESTS ON MC-6 SPECIMENS.
SOURCE: OWN ELABORATION

NOMBRE	$\sigma_{máx}$ (N/mm^2)	$\varepsilon_{máx}$ (adim.)	$E_{máx}$ (N/mm^2)	$\sigma_{últ}$ (N/mm^2)	$\varepsilon_{últ}$ (adim.)	$E_{últ}$ (N/mm^2)
MC-6-5A	6,275	0,024	0,102	1,030	0,085	0,321
MC-6-5B	5,748	0,020	0,081	0,567	0,070	0,246
Medios	6,011	0,022	0,091	0,799	0,077	0,284

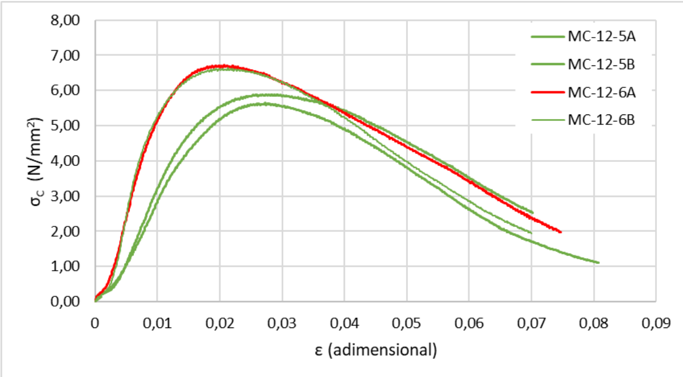

Fig. 16. Compressive graphs of MC-12 specimens. Source: Own elaboration

TABLE XIII
RESULTS OF COMPRESSIVE TESTS ON MC-12 SPECIMENS.
SOURCE: OWN ELABORATION

NOMBRE	$\sigma_{máx}$ (N/mm²)	$\varepsilon_{máx}$ (adim.)	$E_{máx}$ (N/mm²)	$\sigma_{últ}$ (N/mm²)	$\varepsilon_{últ}$ (adim.)	$E_{últ}$ (N/mm²)
MC-12-5A	5,891	0,026	0,094	2,530	0,070	0,295
MC-12-5B	5,642	0,027	0,094	1,101	0,081	0,274
MC-12-6A	6,715	0,021	0,092	1,978	0,075	0,337
MC-12-6B	6,635	0,021	0,095	1,683	0,070	0,313
Medios	6,221	0,024	0,094	1,823	0,074	0,305

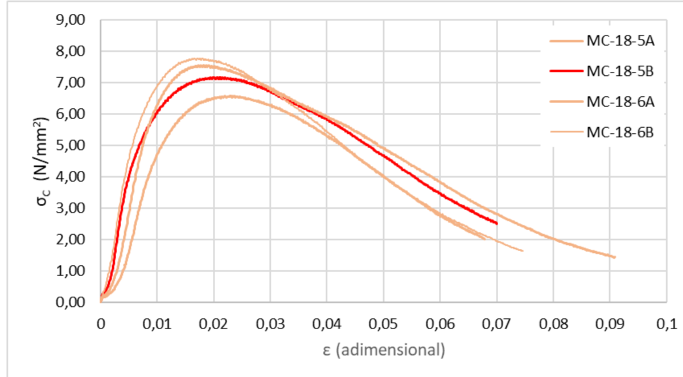

Fig. 17. Compressive graphs of MC-6 specimens. Source: Own elaboration

TABLE XIV
RESULTS OF COMPRESSIVE TESTS ON MC-6 SPECIMENS.
SOURCE: OWN ELABORATION

NOMBRE	$\sigma_{máx}$ (N/mm²)	$\varepsilon_{máx}$ (adim.)	$E_{máx}$ (N/mm²)	$\sigma_{últ}$ (N/mm²)	$\varepsilon_{últ}$ (adim.)	$E_{últ}$ (N/mm²)
MC-18-5A	6,587	0,023	0,098	2,006	0,068	0,300
MC-18-5B	7,173	0,021	0,111	1,078	0,070	0,358
MC-18-6A	7,562	0,018	0,089	1,427	0,091	0,411
MC-18-6B	7,782	0,018	0,101	1,626	0,075	0,363
Medios	7,276	0,020	0,100	1,534	0,076	0,358

specimens, specimen 6B is taken as representative because it presents intermediate maximum stress values and acceptable unit strain values. In the strain energy density, it presents a value more distant from the mean than others, which is due to the fact that it also has a somewhat lower maximum unit strain (Fig. 14 and Table 11).

In the specimens with fibre lengths of 6 mm, only two halves are available; the other two were lost during the tests due to an error in the programming of the machine. As only two specimens were analysed, it is more complicated to decide which one best represents the model; in this case, the MC-6-5B was chosen (they are shown in Fig. 15 and table 12).

Four graphs have been extracted from the following case. They are clearly differentiated two by two, each one belonging to the same prismatic specimen. One of the two halves belonging to specimen number 6 is taken as a reference because they are more similar to each other than those of specimen number 5, as can be seen in the attached graph and table (Fig. 16 and Table 13).

With the 18 mm fibres, graphs are obtained that can also be differentiated two by two in shape, while those of specimen 5 have a smoother appearance, those of specimen number 6 have a shape with a higher peak and post-peak drop (Fig. 17). If we look at the mean values in the table we can see a more similar shape to these, therefore MC-18-5B is set as representative (Table 14).

In the test with the MC-24 specimens, one of them, the MC-24 6A, has values practically equal to the average in terms of maximum unit strain and maximum strain energy density, which is why it was decided to choose it as the characteristic

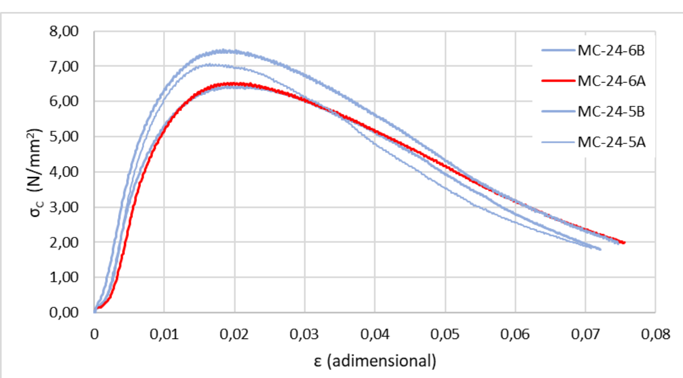

Fig. 18. Compressive graphs of MC-24 specimens. Source: Own elaboration

TABLE XV
RESULTS OF COMPRESSIVE TESTS ON MC-24 SPECIMENS.
SOURCE: OWN ELABORATION

NOMBRE	$\sigma_{máx}$ (N/mm²)	$\varepsilon_{máx}$ (adim.)	$E_{máx}$ (N/mm²)	$\sigma_{últ}$ (N/mm²)	$\varepsilon_{últ}$ (adim.)	$E_{últ}$ (N/mm²)
MC-24-5A	7,071	0,016	0,074	1,835	0,071	0,316
MC-24-5B	7,469	0,018	0,095	1,958	0,075	0,364
MC-24-6A	6,530	0,020	0,088	1,995	0,076	0,328
MC-24-6B	6,433	0,021	0,096	1,802	0,072	0,314
Medios	6,876	0,019	0,088	1,898	0,073	0,330

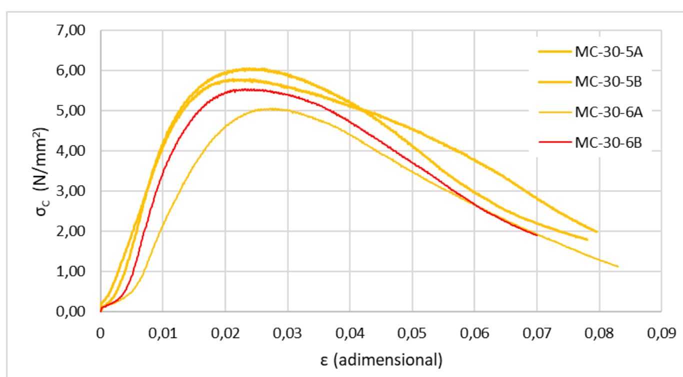

Fig. 19. Compressive graphs of MC-30 specimens. Source: Own elaboration

TABLE XVI
RESULTS OF COMPRESSIVE TESTS ON MC-30 SPECIMENS.
SOURCE: OWN ELABORATION

NOMBRE	$\sigma_{máx}$ (N/mm²)	$\varepsilon_{máx}$ (adim.)	$E_{máx}$ (N/mm²)	$\sigma_{últ}$ (N/mm²)	$\varepsilon_{últ}$ (adim.)	$E_{últ}$ (N/mm²)
MC-30-5A	6,051	0,023	0,088	1,783	0,078	0,310
MC-30-5B	5,778	0,024	0,094	1,991	0,080	0,328
MC-30-6A	5,054	0,027	0,078	1,121	0,083	0,252
MC-30-6B	5,538	0,024	0,080	1,536	0,070	0,262
Medios	5,605	0,024	0,085	1,608	0,078	0,288

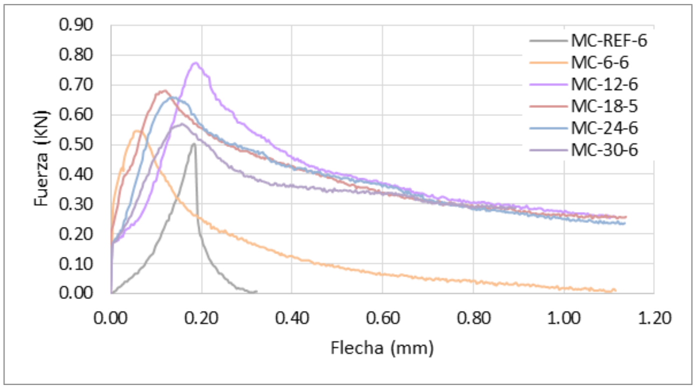

Fig. 20. Comparative Flexural graphs after 180 days. Source: Own elaboration

TABLE XVII
RESULTS OF COMPRESSIVE TESTS ON MC-24 SPECIMENS.
SOURCE: OWN ELABORATION

NOMBRE	$\sigma_{máx}$ (N/mm^2)	$F_{máx}$ (KN)	$\delta_{máx}$ (mm)
MC-REF	0,313	0,501	0,185
MC-6	0,341	0,546	0,069
MC-12	0,484	0,775	0,190
MC-18	0,425	0,679	0,122
MC-24	0,411	0,658	0,144
MC-30	0,356	0,569	0,157

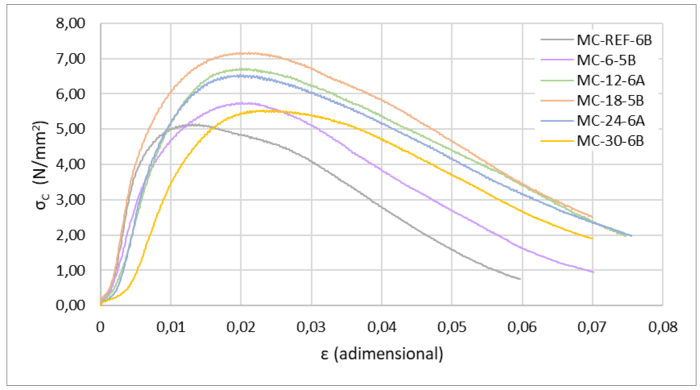

Fig. 23. Comparative 180-day compression charts. Source: Own elaboration

TABLE XVIII
RESULTS OF THE 180-DAY COMPRESSION TEST TO BE COMPARED.
SOURCE: OWN ELABORATION

NOMBRE	$\sigma_{máx}$ (N/mm^2)	$\varepsilon_{máx}$ (adim.)	$E_{máx}$ (N/mm^2)	$\sigma_{últ}$ (N/mm^2)	$\varepsilon_{últ}$ (adim.)	$E_{últ}$ (N/mm^2)
MC-REF	5,141	0,013	0,046	0,749	0,060	0,193
MC-6	5,748	0,020	0,081	0,567	0,070	0,246
MC-12	6,715	0,021	0,092	1,978	0,075	0,337
MC-18	7,173	0,021	0,111	1,078	0,070	0,358
MC-24	6,530	0,020	0,088	1,995	0,076	0,328
MC-30	5,538	0,024	0,080	1,536	0,070	0,262

specimen of the model (Table 15). In addition, it presents a better-looking graph than the two with higher stresses, with a smoother drop (Fig. 18).

For the last of the compression cases, the specimen most similar to the average values in the table is selected to continue the study. Moreover, graphically, it also has an intermediate appearance compared to the rest. This is specimen MC-30-6B and presents maximum stress values of 5.538 KN, unit strain of 0.024 and strain energy density of 0.080 N/mm2 (Fig. 19 and Table 15).

C. Discussion

An analysis of the influence of the presence of basalt fibres in reinforced mortars at a higher age, 180 days, is carried out to confirm the hypotheses of the previous research.

For this purpose, the results obtained in the flexural and compression tests are compared.

In the flexural tests, the characteristic curves of each of the models are represented in the same graph. From this graph, it can be seen how the break with the reference specimen a brittle break is, as the drop after the break is sudden. With the presence of fibres this does not occur, it becomes a ductile break. Moreover, as the length of the fibres increases, this drop in stress is more progressive, so it is once again affirmed that longer fibre lengths favour the ductility behaviour of the mortar. Looking at this same graph and the table, it can be seen that the length of fibres that resists greater force during the test, with greater deflections also achieved, is 12 mm (Fig. 20 and Table 17).

With this in mind, two bar charts comparing these two values are analysed. Fig. 21 analyses the maximum strength, which in the most favourable case is achieved with the 12 mm fibres, the long length specimens such as 18 and 24 mm also show considerably better values than the reference and finally, the 6- and 30-mm fibres which, although they improve the performance of the reference mortars, do not manage to achieve high values.

Finally, Fig. 22 shows the values of the maximum deflections achieved. The trend in the reinforced specimens is that, as the length of the fibres increases, the maximum deflection also

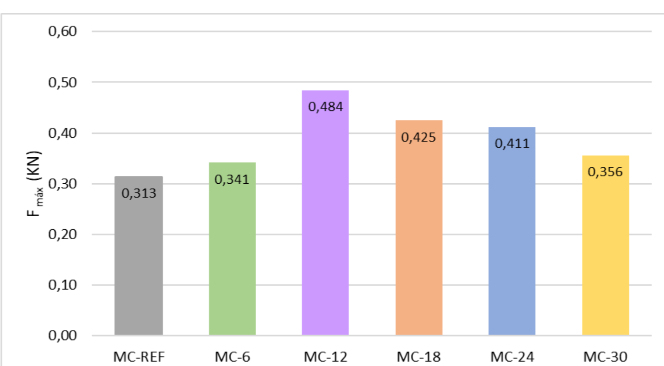

Fig. 21. Comparison of maximum strength values in bending tests at 180 days. Source: Own elaboration.

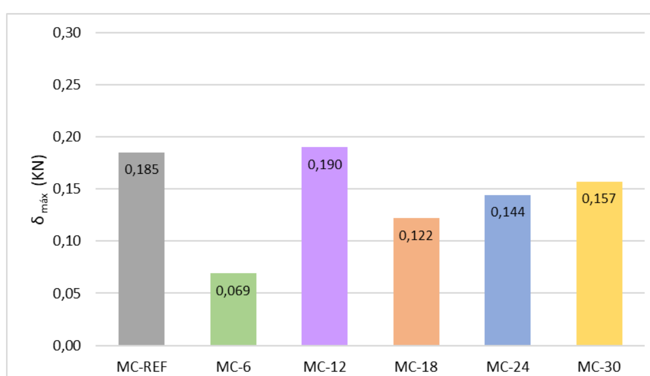

Fig. 22. Comparison of maximum deflection values in bending tests at 180 days. Source: Own elaboration.

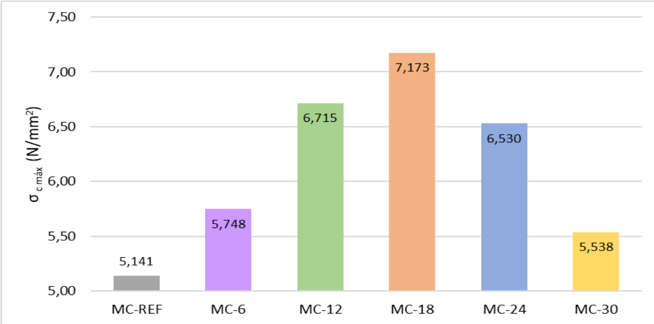

Fig. 24. Comparison of maximum compressive stress at 180 days. Source: Own elaboration.

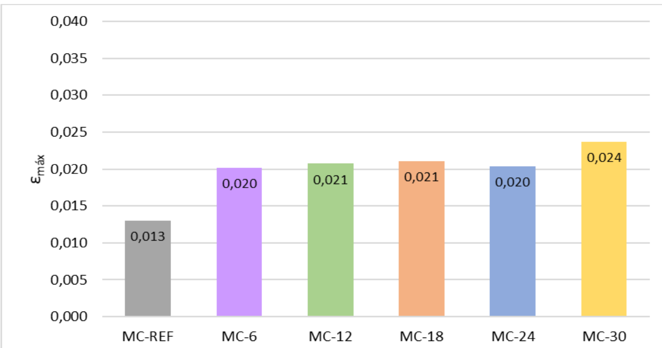

Fig. 25. Comparison of maximum unit strain in compression at 180 days. Source: Own elaboration.

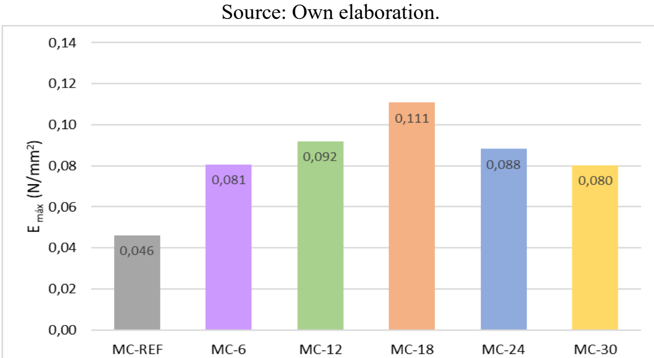

Fig. 26. Maximum strain energy densities in compression at 180 days. Source: Own elaboration

increases, with another outstanding value being achieved with the specimens reinforced with 12 mm long fibres.

After observing these comparisons, we proceed to analyse the results obtained in the compression test.

In the comparative graph of all the lengths, the same occurs as in bending, the graphs have smoother drops after rupture as the fibre lengths increase, the drop being more abrupt or rapid for the reference mortar. It can also be seen how the presence of fibres makes the graphs larger, highlighting the difference between the reference and the 18 mm graph, which is the largest graph (Fig. 23).

The characteristic values of the test are then analysed and are shown in Table 5.2. The maximum values are taken and plotted in bar charts for comparison. In the maximum stress value, the value obtained with 18 mm fibres can be highlighted, followed closely by the 12 mm fibres and then by the 24 mm fibres. In this sense, it could be said that with long fibre lengths, higher compressive stresses are achieved, up to 30 mm, with which there is a drop in stress, so that they would not work well (Fig. 24).

No relationship can be extracted from the unit deformation, except that it improves with the presence of fibres and that those of 30 mm in length stand out, the rest are very similar values (Fig. 25).

Finally, the strain energy density parameter is analysed as a way of estimating which mortars would be more ductile or absorb more energy during the test until failure. It is somewhat related to the maximum test stress as the relationships that follow between the different lengths are the same. Reinforced mortars absorb more energy than reference mortars (worse behaviour by far). Within the reinforced mortars, the energy absorbed increases with increasing fibre length until the most favourable value is reached for specimens with basalt fibres of 18 mm length. From this point onwards, the amounts of absorbed energy decrease again and remain above the reference values (Fig. 26).

Analysing all these results, two fibre lengths that behave better at 180 days are the 12 mm fibres in bending and the 18 mm fibres in compression, their behaviour being quite similar and with little disparity between the two. They have similar shapes in the graphs and also acceptable characteristic values in either case.

For all these reasons, it was decided to continue the research with 12 mm long basalt fibres, since it is one of the fibres that best affects the behaviour of the mortar. In addition to this, because the behaviour is similar, the results of the previous research carried out at 28 days are reviewed, and it is found that the 12 mm fibres stand out in all aspects over the 18 mm fibres.

IV. Conclusions

This research aims to demonstrate the most suitable fibre length to be used in a hydraulic lime mortar by analysing its behaviour at ages greater than those stipulated in the standard, 180 days compared to the 28 days stipulated in the standard.

The conclusions derived from the experimental process carried out are indicated below:

- From the study at 180 days on the mechanical behaviour of a hydraulic lime mortar reinforced with basalt fibres of different lengths, it is concluded that at ages higher than 28 days, the fibres continue to have a favourable effect on the mechanical behaviour of the mortar.
- - The reinforced mortars were found to achieve higher flexural and compressive strengths than the reference mortars with all the fibre lengths analysed, with two lengths longer than the rest.
- - Based on previous studies and this first part of the work, it can be concluded that the most suitable length for adding basalt fibres to provide a hydraulic lime mortar for structural purposes is 12 mm.

As a final conclusion, it can be stated that basalt fibres of 12 mm in length are still the best when it comes to analyse the mechanical behaviour of a reinforced hydraulic lime mortar at 180 days.

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