Revised manuscript (clean version)

<ICCMS_López-Ausín>

[Construction Materials and Structures, ICCMS-2022]

Modification of shrinkage and mechanical properties of concrete by the addition of ladle furnace slag (LFS)

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Abstract

The decrease in humidity in a concrete element due to a difference in relative humidity between the surrounding environment and the element itself causes a volumetric deformation, which leads to a decrease in volume. This phenomenon, called shrinkage, can lead to the appearance of cracks in the concrete, which in turn can cause a decrease in the strength and durability of the structural element. One strategy to reduce shrinkage could be the addition of Ladle Furnace Slag (LFS) during concrete production, as this type of slag has expansive properties due to the presence of free lime and magnesia. LFS is a by-product of the steel industry, so its use in concrete production also has a beneficial effect on the environment by removing waste from the production chain. As the addition of LFS leads to a variation in the mechanical properties of concrete apart from a decrease in shrinkage, it is convenient to accurately evaluate the modification of all these properties when adding different proportions of LFS. The final aim is to define the optimum amount of LFS that can be added to reduce shrinkage while maintaining the mechanical properties of the concrete above the required limits. To do so, this research work evaluates the modification of shrinkage up to 90 days from concrete production, as well as the variation of two key mechanical properties, compressive strength and flexural strength, at two different curing ages, 28 and 90 days, when LFS in proportion of 5%, 10% and 20% is added to the concrete mix as cement addition. A reference mix was designed with a slump of about 70 mm and the other three mixes were defined by replacing the fine aggregate with LFS in the proportions referred and adjusting the water content to reach a slump equal to 80±15 mm. The results showed a decrease in shrinkage when LFS was added to the concrete mix, although the water content of the concrete mix also played a key role. It was also found a modification of the compressive strength and flexural strength, which was related to the proportion of LFS added. Finally, it was also noted that the strength increased quicker when a lower proportion of slag was used.

Keywords: ladle furnace slag, mechanical properties; shrinkage; sustainability

1. Introduction

The decrease in humidity in a concrete element due to a difference in relative humidity between the environment and the element itself causes a volumetric shrinkage deformation (decrease in volume) which is called drying shrinkage. Drying shrinkage occurs over time and whenever there are differences in humidity. As a result of this decrease in volume, cracks may appear in the concrete element, which may lead to a decrease in the strength and durability of the concrete element, as the resistance to carbonation and chloride attack of the concrete element decreases, which facilitates corrosion of the reinforcement and a consequent decrease in the cross-section of the reinforcement. When this occurs, it becomes necessary to repair the affected structural element or even, with the environmental impact that this entails, to destroy it and replace it with a new element. For this reason, it is particularly important to validate different strategies to reduce or even avoid the shrinkage phenomenon so that future concrete elements have a longer useful life and to reduce the consumption of natural resources, increasing the sustainability of the construction sector.

If concrete elements could shrink freely, there would be no cracks [1], but on the one hand they are limited by the surrounding structure, which causes macro-cracks, and on the other hand they have an internal limitation that leads to micro-cracks. This internal limitation is due firstly to the internal moisture gradient in the element itself and secondly to the limitation to shrinkage by the aggregates. In fact, the origin of shrinkage is in the cement paste. The presence of

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aggregates in the concrete limits the deformations, the higher the aggregate/cement ratio, although shrinkage increases with the water/cement ratio. Quantitatively, drying shrinkage is 6 to 8 times lower in concrete than in the cement paste. This is because the modulus of elasticity of the aggregates is higher than that of cement paste. Therefore, if the shrinkage in the cement paste can be reduced, the appearance of micro-cracks will also be reduced, and durability will increase.

Although drying shrinkage is the most important shrinkage for a conventional concrete in which the water/cement ratio is less than 0.4 [2], there are other shrinkage deformations such as autogenous shrinkage, which is due to the loss of moisture by the hydration reactions of the cement; plastic shrinkage, which occurs before the hardening of the concrete (during the first 24 hours) and total shrinkage, which includes drying shrinkage and autogenous shrinkage [3]. Therefore, the drying shrinkage for an element cannot be established without considering the autogenous shrinkage of the element.

Numerous strategies to decrease or combat shrinkage have been investigated. These include the partial replacement of cement with pozzolanic materials [4] such as fly ash [5], silica fume [6], slag [7] and many others [4]; the inclusion of carbon-based nanomaterials [8]; the addition of different types of fibers such as polypropylene [9], [10], steel [11] or natural fibers; the use of additives that reduce surface tension or increase expansion, the use of superplasticizers [12] as well as the control of moisture and curing [13].

Among the strategies mentioned above is the use of slag, including Ladle Furnace Slag (LFS). LFS is a by-product of the steel industry generated after the second steel refining process. It has a fine grain size and limited hydraulic reactivity [14], but it changes in volume when affected by atmospheric changes [14]. LFS has in their chemical composition mainly magnesium oxides, dicalcium silicate and free lime, and, to a lesser extent, calcium aluminate. As it presents some very similar oxides to those of clinker, their use as a substitute for Portland cement has been studied in several cases.

This research addresses the use of LFS as an aggregate substitute in concrete elements and as a shrinkage reducing agent.

2. Methodology

The following sections explain the material used, the dosage of the mix and the tests carried out to evaluate the variation in the characteristic of the concrete.

2.1. Materials

Concrete mixes composed of water, natural aggregates, cement, admixtures and LFS in different proportions were produced.

2.1.1. Binders, water, and admixtures

Portland cement CEM II/A-L 42.5 R, with a clinker content of over 95%, was used. Mix water was taken from the water supply network of the city of Burgos, Spain, where the study was carried out. It use was adequate for the production of concrete according to previous experience from the authors [15]. In addition, two different admixtures were used to provide the concrete with the required workability; firstly, a viscosity regulator was used to maintain the flowability for a longer period of time, and secondly, a plasticizer was added to give the concrete the required flowability.

2.1.2. Aggregates

Two different types of natural aggregate were used. On the one hand, a 0/16 mm siliceous aggregate and on the other hand a 0/2 mm limestone sand were used. The 0/16 mm siliceous aggregate had a bulk density of 2.70 Mg/m^3, a 24-hour water absorption of 0.2 %, a Los Angeles coefficient of 27 and a Sand Equivalent of 82 %, while the 0/2 mm limestone sand had a bulk density of 2.67 Mg/m^3, a 24-hour water absorption of 0.1 % and a Sand Equivalent of 57 %.

2.1.3. Ladle furnace slag

Finally, LFS provided by the company Hormigones y Morteros Agote, S.L.U (HORMOR), a company dedicated to the recovery of slag from the manufacture of steel in electric arc furnaces, was used. The LFS had an apparent particle density equal to 2.80 Mg/m^3 and a 24-hour water absorption of 2.0 %.

The granulometry of the aggregates and LFS is shown in Fig. 1. It can be observed that none of them presented discontinuities in their granulometry, which made their use in the elaboration of structural concrete suitable [15].

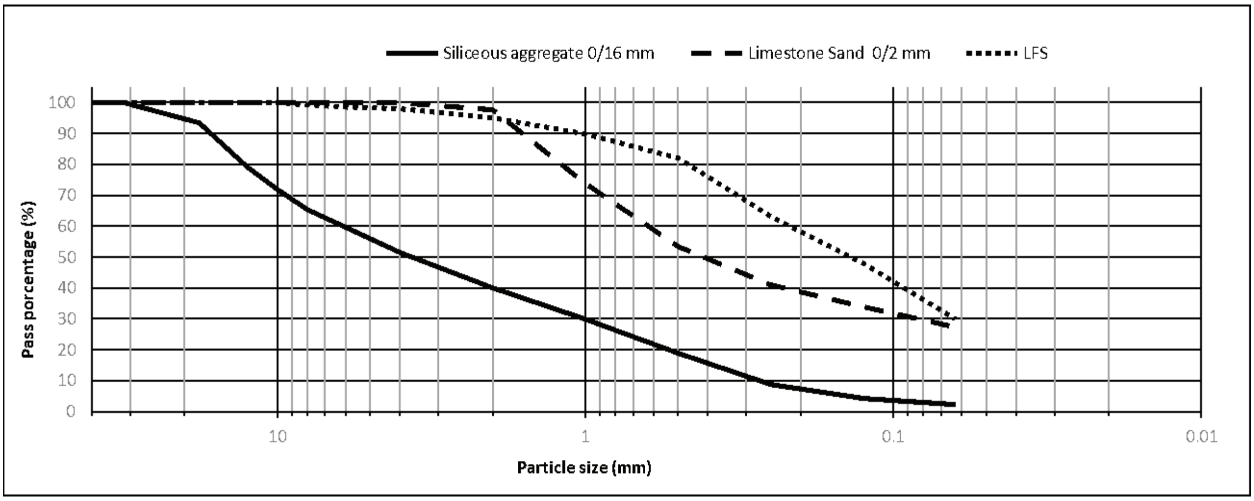

Figure 1. Particle gradation of the aggregates and LFS.

2.2. Mix design

First, the reference mix, called V-0, in which LFS was not incorporated, was defined on the basis of previous experience by the authors and by empirically adjusting the proportion of the different components to achieve a concrete with a slump of around 70 mm. Once this first reference mix called V-0 (with 0 % LFS) was defined, the other mixes were defined by replacing the 0/2 mm limestone sand by weight with 5 %, 10 % and 20 % LFS, and adjusting the water content to compensate for the higher water absorption of LFS and to ensure that the slump remained in the range of 80±15 mm. The mixes were named V-H-5, V-H-10 and V-H-20 depending on the percentage of LFS added (the numerical value refers to the percentage of LFS).

The reference dosage of the V-0 mix was as follows: 320 kg/m^3 cement, 149 kg/m^3 water, 1750 kg/m^3 natural siliceous aggregate 0/16 mm, 320 kg/m^3 natural limestone aggregate 0/2 mm or sand, 2.0 kg/m^3 viscosity regulating admixture and 4.0 kg/m^3 plasticizer admixture. In the V-H-5 mix, 16 kg/m^3 of LFS were added to 304 kg/m^3 of 0/2 mm limestone sand and 151 kg/m^3 of water, while in the V-H-10 mix, 32 kg/m^3 of LFS were added, with 288 kg/m^3 of 0/2 mm limestone sand and 152 kg/m^3 of water; lastly, in the V-H-20 mix, 64 kg/m^3 of LFS were added, with 256 kg/m^3 of 0/2 mm limestone sand and 156 kg/m^3 of water

2.3. Experimental program

The preparation of each concrete mix was carried out in three stages, in order to achieve a correct hydration of all the components of the mix and to avoid the absorption of the admixtures by the aggregates. The mixing stages were as follows:

- In a first stage, all the aggregates (natural siliceous aggregate 0/16 mm and natural limestone aggregate 0/2 mm) were added to the mixer, then the rotation of the mixer was activated and finally, half of the mixing water, previously prepared in a precise manner, was slowly added, and mixed for 30 seconds. The aggregates were in laboratory conditions at a humidity of 45 % and a temperature of 20 Celsius degrees.
- In a second stage, the binder was added, and the remaining water was slowly incorporated. The whole mixture was mixed for another 30 seconds.
- Finally, the admixtures were added, and the whole mixture was mixed for 300 seconds.

Once the mixing process was completed, fresh-state tests were carried out: slump, fresh-density and occluded-air test through the pressure method, according to the standards EN 12350-2, EN 12350-6 and EN 12350-7, respectively. Also, while fresh-tests were carried out, the specimens for the hardened state tests were prepared according to standard

EN 12390-2 by compacting them using a vibrating table. These specimens were left to cure for 24 ± 1 hours at a temperature of 20 ± 5 Celsius degrees and inside a sealed bag. After this time, they were unmolded and stored in a humid chamber or in a drying chamber, depending on the test for which they were intended, where they continued to cure until the moment of the test. Depending on the type of test to be carried out, they were stored under different conditions:

- The specimens for strength tests were stored in a humid chamber at a humidity of 95 ± 5 % and a temperature of 20 ± 2 ºC.
- The specimens for shrinkage measurement tests were kept in a drying chamber at a humidity of 55 ± 5 % and a temperature of 20 ± 2 ºC.

For each test, two specimens were prepared so that the results were obtained as the arithmetic mean of two experimental measurements.

The different hardened tests carried out together with the type of specimens used and the standards followed for each test are shown in Table 1.

Table 1. Hardened tests. Standards and types of specimens.

Test	Standard	Type of specimens used *(mm)*
Compressive strength	EN 12390-3	Cylindrical test tube 100x200
Flexural strength	EN 12390-5	Prismatic test tube 75x75x285
Shrinkage	EN 12390-16	Prismatic test tube 75x75x275

The measurement of total shrinkage was carried out over two points along the main axis at the ends of the specimen and was performed inside the drying chamber so as not to alter the conditions of the specimens. Shrinkage was measured every day during the first 11 days from the preparation of each mix, then every 4 days until an age of 28 days, and then every week.

3. Results and discussion

In this section, the results of all the different test performed to the specimens will be presented. This includes the fresh-state tests performed just after the mixing and the hardened tests performed at different ages to the different specimens prepared.

3.1. Fresh properties

After the mixing process, fresh-state tests were carried out to evaluate the slump, density, and air content of each mix. The results obtained are shown in Table 2.

Table 2. Fresh properties. Standards and types of specimens.

Test	V-0	V-H-5	V-H-10	V-H-20
Slump *(cm)*	7.5	7.0	6.5	9.5
Fresh density *(g/cm^3)*	2408	2414	2408	2397
Air content (%)	1.4	1.5	1.7	1.9

The slump test is used to determine the consistency of the concrete in its fresh state, and it was carried out using the Abrams cone. The result of the slump test is the difference in height between the height of the cone and that of the concrete mass after lifting vertically the cone in which it was contained, provided that the concrete is approximately symmetrical and without lateral mass drop.

The slump value obtained in all the mixes is very similar with a value equal to 80±15 mm. According to their slump values, the three mixtures had a S2 consistency, in the same range of 50-90 mm.

The fresh density of the three mixtures was practically the same with a maximum deviation from the average value of less than 0.4 %. This shows the adequate preparation of each of the mixtures, according to the foreseen dosage.

Finally, the percentage of air content was also very similar for all the mixes.

3.2. Hardened state tests

In order to check the variation of the mechanical properties of the concrete in relation to the percentage of LFS replacing the fine aggregate, several tests were performed at ages of 28 and 90 days. The value of 90 days was chosen because the strength at an age of 90 days for a specimen stored in a humid chamber is very similar to the strength value in the long term in an ambient-cured real structure as it was established in previous research by the authors [16].

3.3. Compressive strength

Compressive strength test measures the maximum axial stress that a concrete specimen can withstand before breaking. It is the most important mechanical characteristic of concrete, so much so that the standard classification of concrete is made on the basis of the minimum simple compressive strength that it must have at an age of 28 days.

The simple compressive strength of the specimens was measured at 7, 28 and 90 days, and the results obtained are shown in Fig. 2.

The results showed a higher strength of the mixes with LFS compared to the reference mix V-0 at the beginning of the curing, age of 7 days, and at an age of 28 days. At 7 days, the V-H-5 mix (37.4 MPa) presented a higher strength than the rest of the mixes, with a value for the reference mix V-0 equal to 34.5 MPa. At 28 days, V-H-5 and V-H-10 mixes presented the highest strengths, with similar values.

Regarding the compressive strength at an age of 90 days, which can be compared to the real compressive strength during the element´s life [16], all the mixes presented similar behaviors, in the interval of 41-43 MPa.

As for the evolution with age, it was observed that the mixes with a low proportion of LFS present a quite constant behavior after 28 days, while the reference mix V-0 presented a delayed acquisition of strength, compared to the LFS-mixtures.

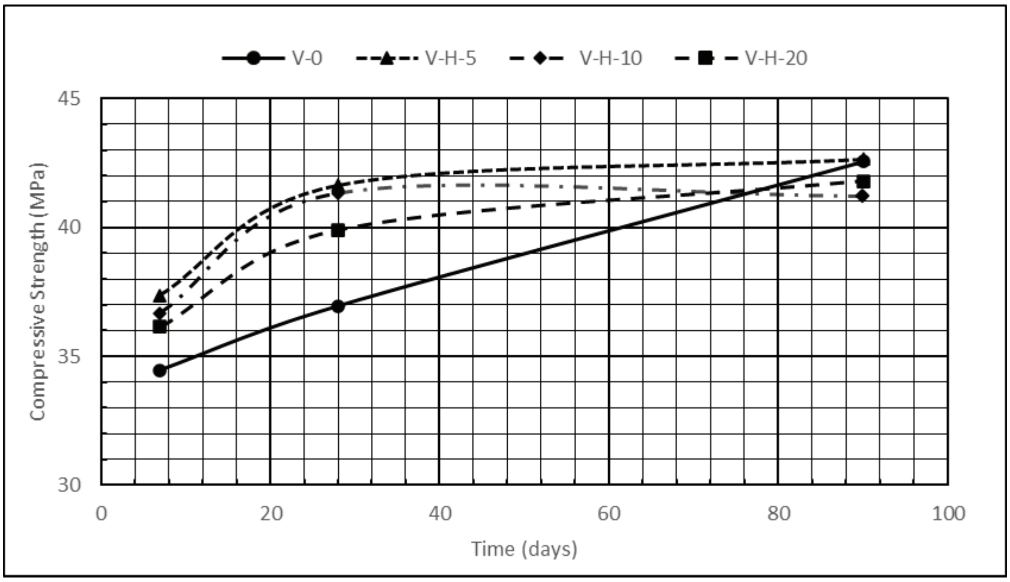

Fig. 2. Compressive strength at ages of 7, 28 and 90 days.

3.4. Flexural strength

The flexural strength test measures the maximum bending stress that a prismatic specimen can withstand before failure, understanding this stress as the load multiplied by the distance between the lower supports of the specimen and divided by the product of the distances between the load application rollers and the support rollers.

The flexural strength of the specimens was measured at ages of 28 and 90 days and the results are shown in Fig. 3. Going beyond the standard, flexural strength was measured also at 90 days to know if a variation in flexural strength could be expected during the service life of the concrete as the value at that age is almost equal to the value during the element's life [16].

The flexural strength shows a similar behavior to the compressive strength. The results showed a higher strength of the mixes with LFS compared to the reference mix V-0. At 28 days, the V-H-20 mix (6.7 MPa) presented a higher strength than the V-H-10 mix (6.4 MPa), the V-H-5 mix (6.0 MPa), and than the V-0 reference mix (5.3 MPa). At 90 days, it was again the V-H-20 mix (7.1 MPa) that presented a higher strength, followed by the V-H-10 mix (6.6 MPa) and with similar values between the V-H-5 mix (6.4 MPa) and the V-0 reference mix (6.3 MPa).

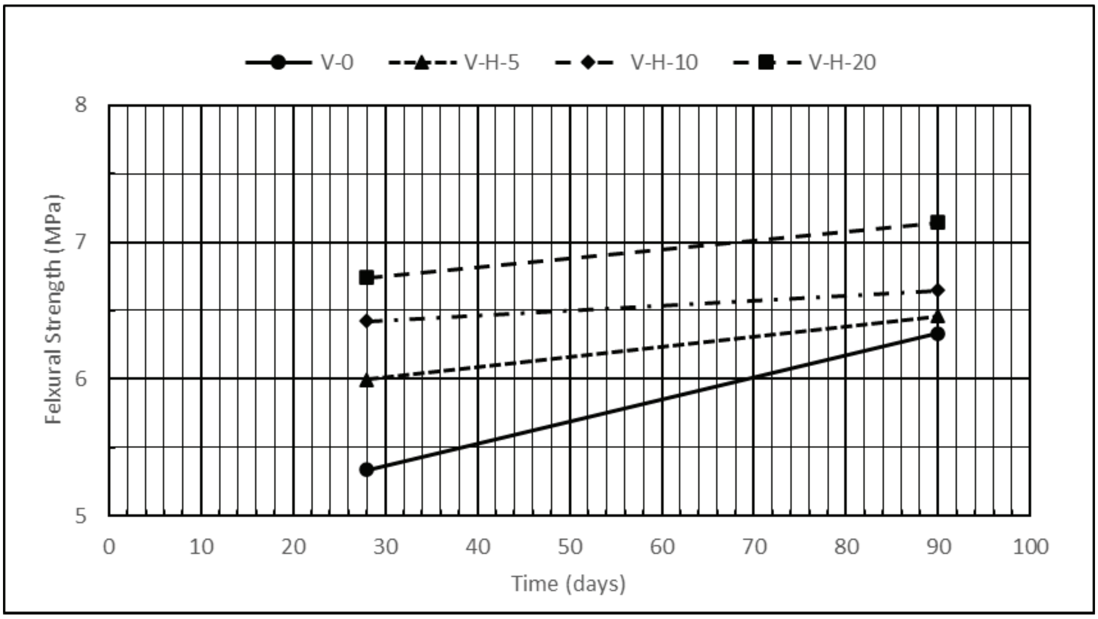

Fig. 3. Flexural strength at ages of 28 and 90 days.

3.5. Shrinkage

Shrinkage was obtained by measuring the difference in length of the specimen with respect to its initial dimension. The total shrinkage results, see Table 3 and Fig. 4, showed a decrease in shrinkage in the V-H-5 mix with respect to the V-0 reference mix, while the V-H-10 and V-H-20 mixes showed an increase in shrinkage with respect to the V-0 reference specimen. This is due to the fact that in a small quantity, mix V-H-5, the LFS totally compensated with their expansion the greater shrinkage caused by the greater quantity of water available, and even reduce it, while in mix V-H-20 this greater shrinkage was not compensated. It should be remembered that in order to maintain the workability of the mix, the amount of mixing water was increased by increasing the amount of LFS to replace the fine aggregate.

Table 3. Total Shrinkage values at different ages

Age	V-0	V-H-5	V-H-10	V-H-20
7 days (%)	-0.174	-0.145	-0.147	-0.172
28 days (%)	-0.288	-0.299	-0.364	-0.411
90 days (%)	-0.348	-0.337	-0.393	-0.438

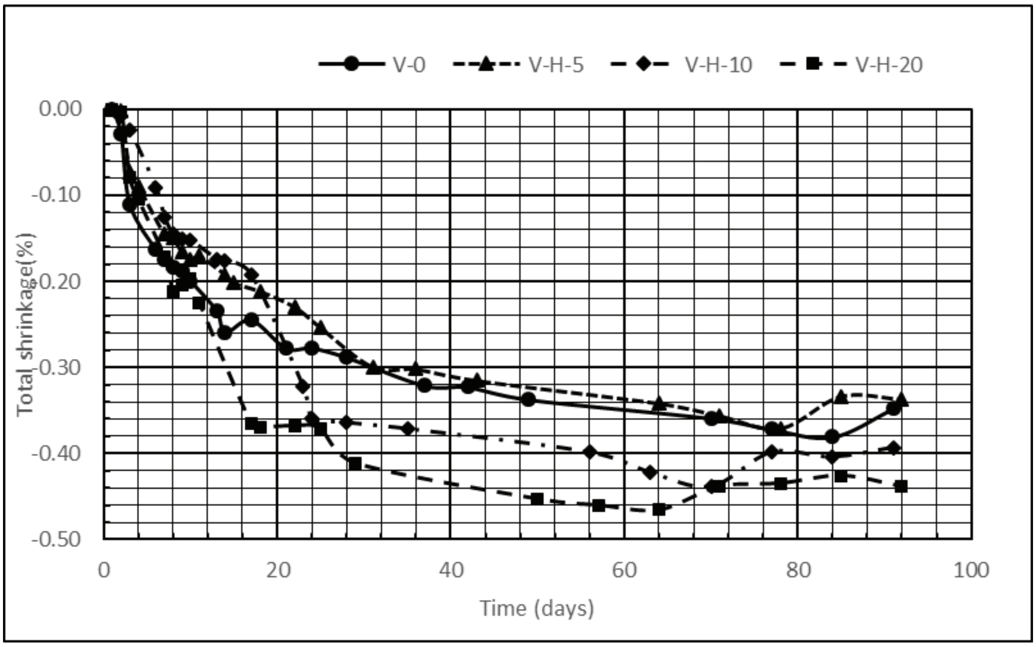

Fig. 4. Total shrinkage from 0 to 90 days.

4. Conclusions

As a corollary, the following can be stated:

- The replacement of part of the fine aggregate in the mix with LFS has not led to a decrease in the mechanical strength of the concrete.
- A higher addition of LFS leads to a higher improvement of the mechanical strengths, both in compression and in flexural strength.
- The mixes with LFS showed a rapid strength gain, which increased very little over time.
- The replacement of a 5% of the fine aggregate by LFS improved shrinkage, with a minor decrease in volume, but increased it for high quantities of LFS as can be seen for 10 and 20% of replacement.
- It is therefore concluded that the use of LFS as an aggregate replacement in concrete elements has a beneficial effect on the mechanical characteristics at any age, causing an increase in mechanical characteristics, but its usefulness as a shrinkage reducing agent is limited as its use in large proportions increases shrinkage.

Acknowledgements

This research work was supported by the Spanish Ministry of Universities, MICINN, AEI, EU, ERDF and NextGenerationEU/PRTR [grant numbers PID2020-113837RB-I00; 10.13039/501100011033; TED2021-129715B-I00] and, finally, the University of Burgos [grant number SUCONS, Y135.GI].

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