Reuse of sheep wool fibers in the production of ultralightweight foamed concrete: effect of fiber treatment, length, and content on the mechanical properties

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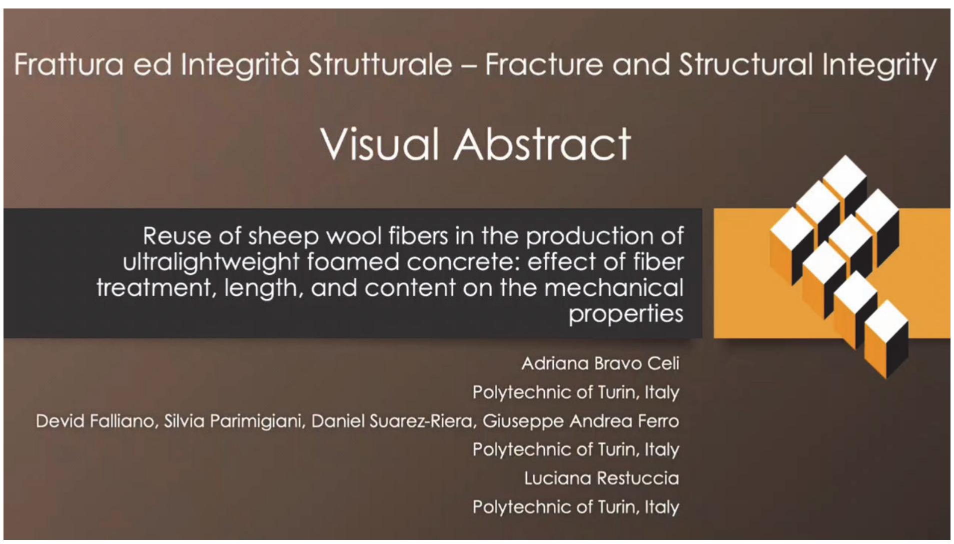

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INTRODUCTION

Concrete is a widely diffused material due to its competitiveness and durability; unfortunately, it is also one of the most pollutant materials in the world: in fact, it is responsible for approximately 8% of global anthropogenic greenhouse gas emissions and 3% of global energy demand [1]. During the last decades, research has focused on reducing the environmental impact of concrete. Although it is impossible to reduce emissions to zero, many strategies can contribute. Reducing the total amount of binder means reducing the clinker content, which is the primary pollutant of concrete production [2]. Using foamed concrete effectively reduces the amount of binder on the mix design and provides thermal insulation to reduce the heating and cooling demand [2].

Foamed or cellular concrete is a low-density concrete that contains a series of air voids produced by adding foam to the mortar mix [3]. Its properties, such as lightness, thermal and acoustic insulation, and fire resistance, have caught the attention of the construction sector to create economic and sustainable structures [4]. There are two primary ways of obtaining foamed concrete. The first involves adding a pre-formed foam or mix-forming agent into the cement mix. The second one, autoclaved aerated concrete (AAC), forms by mixing lime, sand, cement, water, and aluminum powder. The last one acts as an expansion agent due to its reaction with cement, forming microscopic hydrogen bubbles, making concrete grow up to five times its original volume, leaving empty voids after evaporation. AAC receives its name because it is steam-cured in a pressurized chamber or autoclave [4].

This research will focus on the first type of lightweight concrete, which, unlike ACC, does not require autoclave curing and consumes less energy during production. As seen before, accomplishing this effect can result from adding a pre-formed foam or a mix-forming agent. The former method, known as the dry foam method, produces a spume with water and a foaming agent by forcing pressurized air into the solution and creating bubbles, in general, of even size of less than 1mm [5]. The latter, known as the wet foam method, consists of spraying a water/foaming agent solution over a fine mesh, which causes pressure to drop across the mix and allows suctioning air from the environment; this creates a 2-5mm bubble size, which is unsuitable for densities below 1100 kg/m³ [6]. Moreover, due to its stability and reachable density advantages, this research will utilize the dry foam method to develop the experiments.

According to its density, cellular concrete can consent to various applications. Ultralightweight concrete, with a 200-600 kg/m³ density, is mainly applied as thermal and acoustic insulation or fire protection due to its low mechanical performance. A 700-1100 kg/m³ density typically produces bricks, blocks, fillers, floor leveling mortars, and non-structural elements. Higher densities such as 1200-1800 kg/m³ support higher loads and, therefore, can be applied to create precast or onsite structural elements and reduce the specific weight of components that require high strength [7].

Fiber addition to a cement paste improves flexural strength and reduces brittleness by adding a ductile or elastic component. Fiber reinforcements are classified by material into four categories: metallic, synthetic, glass, and natural fibers. Metallic steel fibers are not recommended to be applied on lightweight mixes because of their significant mass [8]. Synthetic fibers such as acrylic, aramid, carbon, polypropylene, polystyrene, nylon, and polyester are broadly researched and result in increased productivity of cellular concrete, contributing to avoiding fragile failures and increasing flexural strength. However, some researchers have found a non-significant reduction of compressive strength, limited to a few cases, when adding synthetic fibers to a concrete mix [4]. On the other hand, polymer fiber additions between 2-5% have shown significant improvements in flexural strength that go from 13-70% depending on the curing conditions [9]. Alkali-resistant glass fibers can also help to strengthen foamed concrete. Analyses of glass fibers show higher compressive strength, flexural strength, and elastic modulus performance than polymeric ones [10].

Due to concrete's sustainability issues, research has focused on reducing carbon emissions. For instance, natural fibers can reinforce foamed concrete and replace polymers or glass. These fibers, typically by-products, translate into low or zero CO_2 emissions because they not only have a natural origin but are often the result of recycling or waste recovery processes. Overall, concrete reinforcement natural fibers are plant-derived and consist of hemicellulose, lignin, and pectin [11]. Henequen fibers, for example, have the potential to be widely introduced as a construction material since they have proven to increase the mechanical properties of concrete, mainly when submitted to an alkaline treatment, which encourages a better fiber-matrix interaction [12].

Although there is a vast database on plant-based fibers, scientists started to drive their interest toward animal fibers. Pig hair, for example, applied to regular mortar, shows higher tensile strength than other natural fibers and is an effective crack control mechanism, particularly for plastic shrinkage cracking [13].

Sheep shearing once a year is essential to maintain the animal's health and hygiene; hence, sheep wool is considered renewable. Unfortunately, nearly 75% of the wool produced in Europe, which amounts to 150 million tons per year, is not serviceable in the textile industry and must be sterilized at 130ºC and disposed of as special waste [14]. Therefore, sheep wool has caught the attention of the construction sector to be employed as a sustainable and economical building material. It is mainly applied as thermal insulation inside walls or partitions to improve the energy efficiency of buildings [15].

In the last decade, studies on applying sheep wool as a fiber reinforcement for concrete have revealed encouraging results. The performed tests have used several techniques to treat the fibers and improve their characteristics, including non-treated, water-rinsed, neutral detergent-washed, salt water-dipped, and plasma-treated fibers. Adding sheep wool fibers to mortar or concrete generally increases flexural strength, fracture toughness, and tensile strength, but compressive strength sometimes diminishes [16].

Regarding the treatments found in previous works, washing the fibers improves adhesion with concrete and, therefore, improves mechanical performance [17]. Dipping sheep wool fibers in salt water increases their surface tension, therefore improving adhesion to the cement matrix, causing the concrete to withstand more compressive and flexural strength [17].

The addition of plasma-treated wool fibers increases flexural strength 5% more than the addition of non-treated fibers; however, fracture toughness increments by 300% in both cases [18].

The fiber content rate and the fiber length affect the mechanical properties. For example, some researchers show that a SWF content between 2-3% is optimal, but when applying treated fibers, this trend is reduced to 0.5-1% to achieve a similar resistance capacity [19]. Furthermore, other experimental works show better performances when varying fiber length. For example, short 1mm fibers act only as a filler, and longer fibers of about 20mm create agglomeration. More desirable results were conceivable using a mid-length value of 6mm with up to a 13% fiber content [17].

Tests on adding sheep wool fibers as concrete reinforcement have yet to include its application to foamed concrete. Therefore, this research paper will focus on designing and characterizing the mechanical properties of ultra-lightweight concrete with sheep wool fibers (SWF) submitted to different treatments and variations in fiber content and length. This research highlights how including SWF can improve fresh-state stability and mechanical properties (compressive and flexural strength) of ultralightweight foamed concrete while increasing its sustainability by incorporating residuary natural fibers. In addition, it compares several fiber categories that can improve foam concretes' properties to determine the most performant fiber treatment, length, and content.

The selected treatments had a specific motivation for their application in SWF. For example, NaClTF gave promising results on SWF in the studies by Alyousef et al. and Gadgihalli et al., where it was proven that treating SWF with salt increases the surface tension of the fiber, improving its adhesion to concrete [20]. Alternatively, SWF were treated with lime because in [21] it has been proved that the employment of $Ca(OH)_2$ into the foam (not onto the fibers, novelty proposed in this research) results in improvement of the microstructure of foamed concrete due to a finer and more homogeneous pore structure. Furthermore, Castillo-Lara et al. proved that treating henequen with sodium hydroxide contributes to the material toughness and a better fiber-matrix interaction due to the alkalinity of the treatment [22]; therefore, this research employs an alkaline treatment to study its performance as a treatment for animal fibers. Additionally, a methodology yet to be investigated in other works is proposed, consisting of treating natural fibers with a mixture of water and foaming surfactant to use the fibers as a foam stabilizer. The mixtures presented here are characterized by stability and good mechanical properties, even compared to other research in the relevant literature on foamed concretes at about the same density, compared to which the present ones are also characterized by a lower environmental impact due to the use of natural fibers. Furthermore, these results will be employed in a forthcoming study to analyze the effects of SWF on the mechanical properties and durability of ultralightweight foamed concretes as their density varies.

MATERIALS AND METHODS

The research tested ultralightweight foamed concrete reinforced with sheep wool fibers (SWF) in its fresh and hardened states.

Each concrete mix follows the same ratios to be comparable when performing the experiments. The studied mortar mixes, made with type CEM I 52.5 R cement, have a water/cement (w/c) ratio of 0.33. The pre-formed foam employed was made with a protein foaming agent dissolved in water at a concentration of 5%; its characteristics are reported in Tab. 1. The generated foam had a density of 80 ± 5 g/l, and its quantities varied according to the expected density.

Nature	Appearance	Specific weight	pH
Protein foaming agent	Brown liquid	1.15 ± 0.02 g/ml	6. 75 ± 0.75

Table 1: Characteristics of foaming agent (all data comes from product's datasheet).

The experimental study comprised a set of 33 foamed concrete specimens and was carried out on ultralightweight foamed concrete characterized by a target density of 300 kg/m³.

The best-performing fiber treatment selection process comprised developing six series of three 40x40x160mm specimens each, with a fiber length of 12 mm and a fiber content of 5 kg/m³, equivalent to 0.4% in volume. The first admixture, produced as a reference, did not include fibers (NF); the second included non-treated fibers (NTF); the remaining four are salt-treated fibers (NaClTF), lime-treated fibers (LTF), sodium hydroxide-treated fibers (NaOHTF), and surfactant-treated fibers (STF).

The type of treatment can already be identified in Tab. 2 from the sample denomination. Tab. 2 shows the amounts of cement, water, viscosity-enhancing additive (VEA), superplasticizer (SP), SWF, and foam employed on each admixture and the fresh-state density (FSD) reached.

MIX ID	Cement [kg/m³]	Water [kg/m³]	VEA [kg/m³]	SP [kg/m³]	SWF [kg/m³]	Foam [kg/m³]	FSD [kg/m³]
NF	194.38	64.15	29.16	1.94	-	108.84	398.50
NTF	205.48	67.81	30.82	2.05	5.00	114.58	425.00
NaClTF	202.70	66.89	30.41	2.03	5.00	113.24	420.60
LTF	195.65	64.57	29.35	1.96	5.00	108.70	405.00
NaOHTF	194.81	64.29	29.22	1.95	5.00	108.64	403.00
STF	200.00	66.00	30.00	2.00	5.00	100.00	403.00

Table 2: Admixtures for fiber treatment selection: fiber length 12 mm, fiber content 5 kg/m³.

The fiber treatments used in this study follow specific procedures for each component employed. Tab. 3 shows the procedures followed to treat each type of fiber. All fibers were machine-washed in tap water at 30°C and air-dried for one week before treatment.

Series	Treatment process
NTF	Machine washed in tap water at 30ºC and air-dried for one week.
NaClTF	Immersed for 72h in a 35g/L salt-water solution, rinsed with tap water, and oven-dried at 30ºC for 72h.
LTF	Immersed in a 1% lime-water solution for 2h and oven-dried at 30ºC for 72h.
NaOHTF	Immersed for 1h in a 2% NaOH-water solution, rinsed with tap water, and oven-dried at 30ºC for 72h.
STF	Immersed for 72h in a 3% surfactant-water solution and oven-dried at 30ºC for 72h.

Table 3: Fiber treatment procedures.

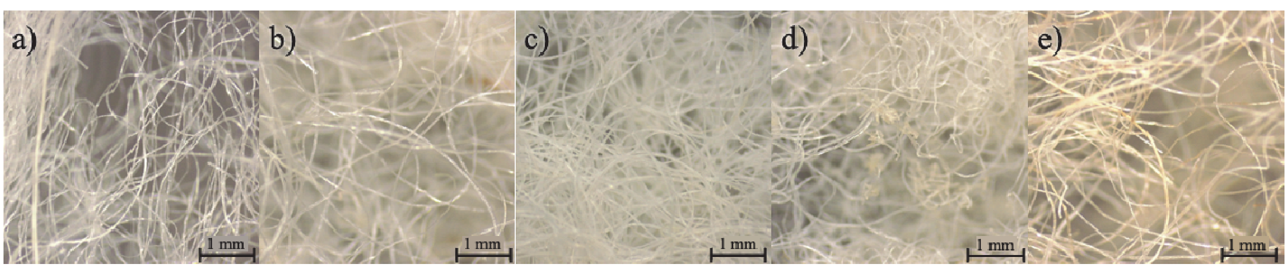

Figure 1: 16x microscope SWF image: NTF (a), NaClTF (b), LTF (c), NaOHTF (d), and STF (e).

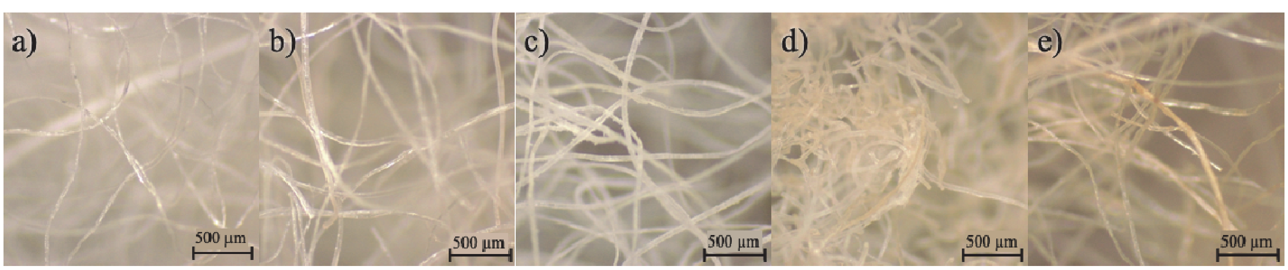

Figure 2: 35x microscope SWF image: NTF (a), NaClTF (b), LTF (c), NaOHTF (d), and STF (e).

Fig. 1 and Fig. 2 show the effects each treatment had on SWF. NTF (a) shows the original state of the fibers after being washed. NaClTF (b) present. LTF (c) presents a roughly crystallized coating covering the fibers, giving them a white color due to the attachment of lime particles to the fibers. NaOHTF (d) shows fiber degradation; in this case, the fibers became rough, fragile, and lost volume due to the acquired frizzy aspect. Finally, STF (e) absorbed the foaming surfactant, assimilating its characteristic brown color and a more opaque and rougher surface.

The best-performing fiber length and content selection process comprised developing five series of three 40x40x160mm specimens each, with NTF. The studied fiber lengths were 6, 12, and 20mm, while the target fiber contents were 5, 10, and 15 kg/m³ (these values are equivalent to a percentage in volume of 0.4, 0.8, and 1.2 % respectively). Therefore, the fiber length study applied a fiber content of 5 kg/m³, while the fiber content study applied a 12mm fiber length. Tab. 4 shows the characteristics of each admixture employed in this selection process. The sample's denomination already identifies length (6, 12, 20 mm) and fiber content (5, 10, 15 kg/m³).

MIX ID	Cement [kg/m³]	Water [kg/m³]	VEA [kg/m³]	SP [kg/m³]	SWF [kg/m³]	Foam [kg/m³]	FSD [kg/m³]
6mm-5	189.87	62.66	28.48	1.90	5.00	105.18	392.84
12mm-5*	203.62	67.19	30.54	2.04	5.00	113.55	422.03
20mm-5	196.94	64.99	29.54	1.97	5.00	110.16	408.52
12mm-10	187.50	61.88	28.13	1.88	10.00	104.03	392.78
12mm-15	178.22	58.81	26.73	1.78	15.00	99.01	382.10

* Admixture employed in both fiber length and fiber content studies.

Table 4: Admixtures for fiber length and fiber content selection.

The first steps for producing the mixtures listed in Tab. 2 and Tab. 4 correspond to the procedure reported in [23]. Moreover, the fibers were applied after the foam to avoid agglomeration during the mixing phase. In particular, the appropriate amount of fibers was added after mixing the foam. Then, high-speed mixing (3000 rpm) was performed for a couple of seconds to achieve dispersion of the fibers in the mixture while avoiding clumping.

The described process was performed using a vertical mixer at 3000 rpm. High mixing intensities reduce pore dimensions in foamed concrete, contributing to its mechanical strength [24]. Moreover, high-speed mixed foamed concrete's tiny and homogenously distributed bubbles result in better performance of the concrete mix [25].

After completing each mixture, the JGJ/T 341–2014 test method was used to assess the workability [21]. In addition, three 40 mm x 40 mm x 160 mm prismatic specimens were cast to perform the 28-day mechanical tests, compressive and flexural strength. The 28-day curing occurred in air condition at room temperature of 20±3ºC and relative humidity of 60±5%.

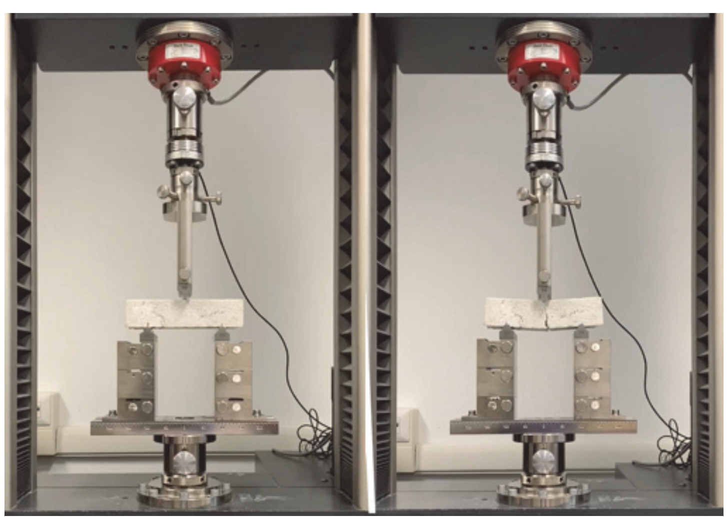

Figure 3: Sample positioning for flexural strength tests.

TESTING CONDITIONS

The workability of the cementitious conglomerates was carried out according to the JGJ/T 341–2014 standard [21]. The slump was measured for each admixture after the material from an 80mm height and diameter cylinder stabilized.

The flexural strength tests were conducted according to the UNI EN 196-1 standard, with a force control of 50N/s.

For the compressive strength tests, the force control mode was used according to the UNI EN 196-1 standard; unlike it, a force control equal to 100 N/s was applied. Given the characteristics and specifications of the material under analysis, very low compressive strengths were expected.

RESULTS AND DISCUSSIONS

Fresh state: Workability

After the mixing process, workability was assessed using the JGJ/T 341–2014 test protocol. Fig. 4 presents the outcomes of slump tests conducted for each admixture. Additionally, each figure reports the error bars, providing a visual representation of the dispersion inherent in the experimental data, thus offering insights into the variability of the results.

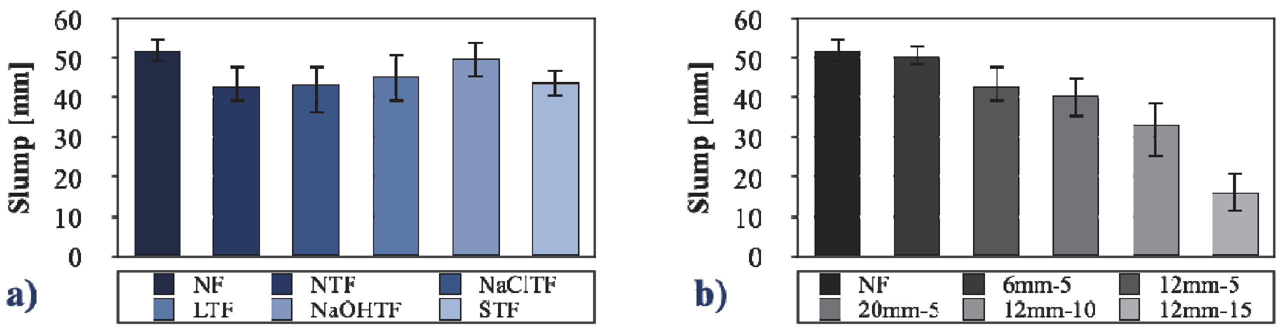

Figure 4. Slump test: a) fiber treatment selection 12mm length and 5kg/m³ content b) fiber length and fiber content selection NTF.

In Fig. 4a, it is evident that the incorporation of fibers yields a notable reduction in slump by an average of 15%. Notably, adding NaOHTF to the admixture demonstrates a slump decrement of 4.5%, a value slightly below the average observed for the other fiber treatments. This reduction can be attributed to the degradation induced in the fibers by the Sodium Hydroxide treatment, resulting in shortened lengths and increased brittleness (Fig. 1 and Fig. 2). These alterations adversely impact the mixture's workability, emphasizing the complex relationship between fiber treatment techniques and their subsequent impact on concrete properties.

In addition, the fiber length study (Fig. 4b) shows that longer fibers translate into a lower slump value. Specifically, the inclusion of 12mm fibers results in an 18% decrease in slump compared to the admixture without fibers, while 20mm fibers lead to a 22.4% reduction. In contrast, the addition of 6mm fibers only shows a 3% reduction in the slump value.

Moreover, the slump tests for fiber content (Fig. 4b) indicate that as the fiber content increases, there is a corresponding decrease in the slump of 18%, 36.5%, and 69.2% in the admixtures with 5, 10, and 15 kg/m³ fiber content, respectively. However, it is essential to note that higher fiber contents lead to agglomerations (view Fig. 5) during the mixing process, affecting the workability and homogeneity of the cementitious matrix. Therefore, using a fiber content as high as that of admixture 12mm-15 for future applications is not advisable.

Mechanical properties: Flexural Strength

The incorporation of fibers into a cementitious matrix typically enhances the flexural strength of concrete, largely due to the mechanical properties of the fibers. Notably, sheep wool fibers exhibit a tensile strength of about 390 MPa [3] and an elastic modulus ranging from 1 to 4 GPa, comparable to that of synthetic plastic fibers [16]. This similarity suggests that wool fibers could provide a viable, more sustainable alternative for reinforcing concrete while maintaining performance characteristics associated with conventional plastic fiber reinforcements.

The flexural strength (σ_f) is reported in Fig. 6 and Fig. 7 in relation to the dry density of the specimens. Additionally, both figures include the error bars to indicate the dispersion of the experimental findings. It is important to mention that all tested specimens' dry density falls within the range of 270 ± 30 kg/m³.

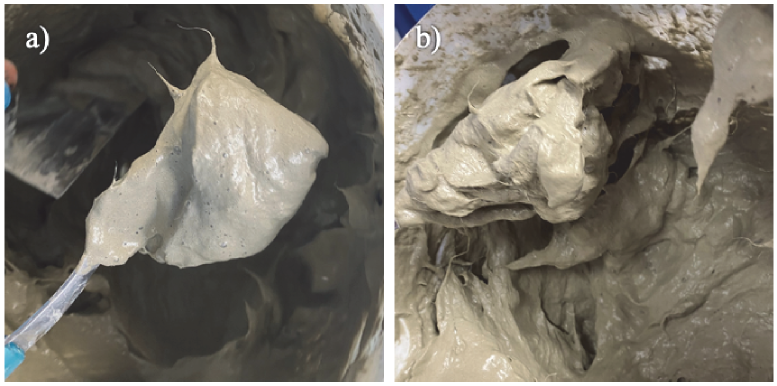

Figure 5: Foamed concrete mix with homogeneous fiber distribution (a) and foamed concrete mix with fiber agglomeration (b).

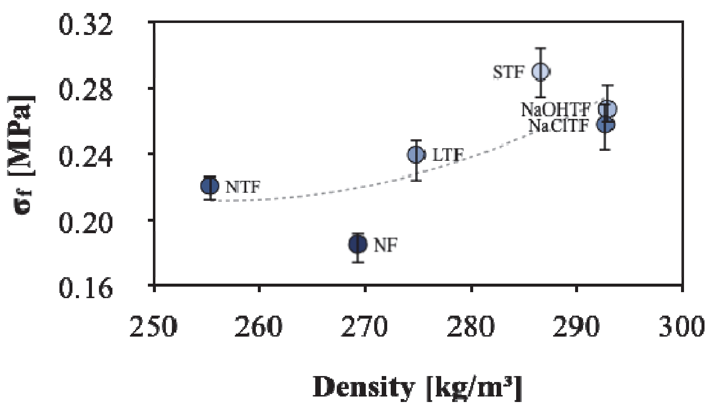

Figure 6: Effect of wool fiber treatment on the flexural strength of ultralightweight foamed concrete.

Fig. 6 illustrates the impact of fiber treatment on the flexural strength of fiber-reinforced ultra-lightweight foamed concrete. It was observed that adding wool fibers enhances the flexural behavior of ultralightweight foamed concrete. When considering only fiber-reinforced specimens, it is noticed that as the density increases, so does the flexural strength, except for samples from the NaOHTF and NaClTF admixtures. Despite having a higher density than STF, these samples exhibit lower flexural strength.

The concrete samples containing STF demonstrated the highest average flexural strength, exhibiting a 61% increase compared to those without fibers. This improvement can be attributed to the microstructure resulting from the enhanced stability of the system. The target density is achieved with a reduced amount of foam in the mix design (Tab. 2) due to the presence of surfactant molecules on the surface of the fibers.

The admixtures treated with salt and sodium hydroxide increased 45% and 50%, respectively. Despite the limited elasticity of the fibers, the NaOHTF achieved the second-highest average flexural strength. LTF mixtures followed with a 33% improvement from the original non-fiber reference mix. In addition, the NTF admixtures demonstrated the lowest increase rate of 22%, which may be attributed to the lower density of these specimens, falling within an acceptable range.

As shown in Fig. 7, the flexural behavior of the samples reinforced with SWF exhibited a more ductile nature than those without fibers. However, it was noted that the NaOHTF samples did not demonstrate a significant improvement. This could be attributed to the treatment, causing damage to the fibers, consequently degrading their elasticity. Notably, the wool fibers became excessively stiff and brittle after the NaOH treatment. Furthermore, Fig. 7 illustrates that the specimens with NTF exhibit the lowest post-peak decrement, resulting in the highest residual strengths.

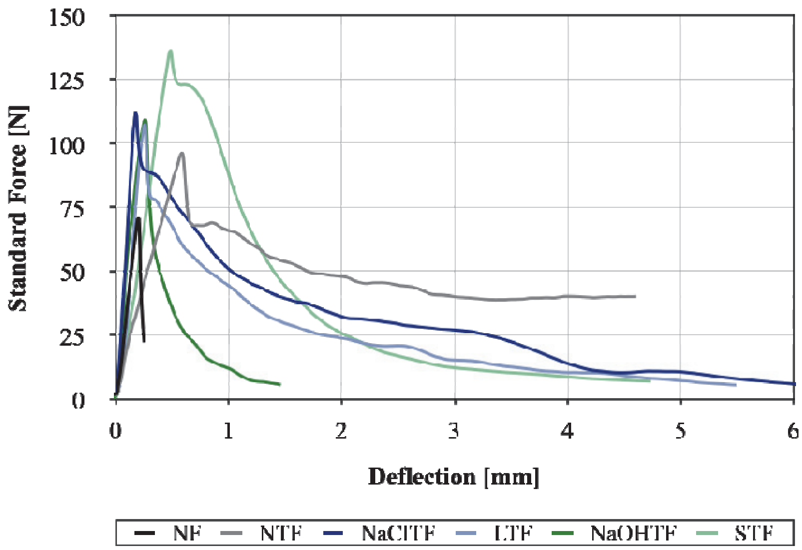

Figure 7: Effect of wool fiber treatment on the flexural behavior of ultralightweight foamed concrete.

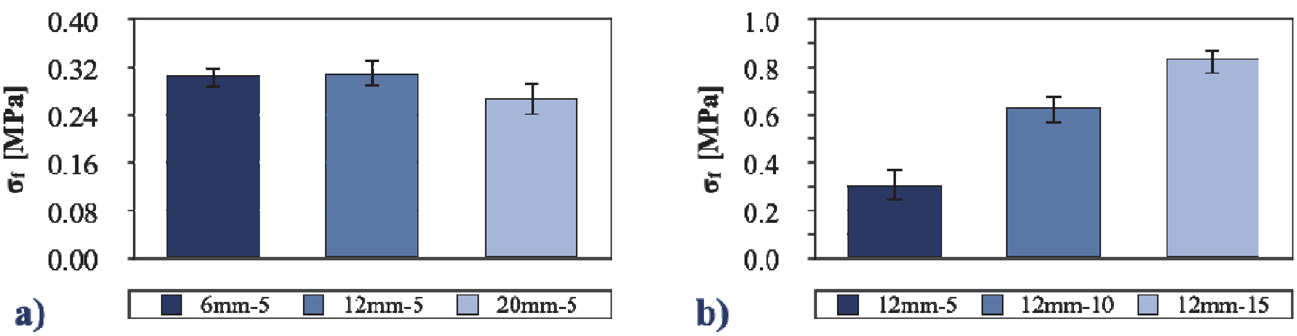

Figure 8: Effect of wool fiber length on flexural strength (a); effect of wool fiber content on flexural strength (b).

The fiber length and content study did not present significant dry density variations.; therefore, the analysis focuses on mechanical strength. Fig. 8a shows the impact of wool fiber length on the flexural strength of ultralightweight foamed concrete. This investigation, along with the analysis of the influence of fiber content shown in Fig. 8b, was conducted on untreated wool fibers. Furthermore, Fig. 8a also indicates that the actual dry densities of different series are closely related. Together with the flexural behavior described below, these results led to choosing 12 mm as the optimal length for wool fibers to be used in foamed concrete.

Fig. 9 shows that mixes with 12 mm and 20 mm fibers show similar flexural behaviors. In comparison, the samples with 6mm fibers have a more brittle behavior. The flexural strength is 13% higher in the 6 and 12 mm admixtures compared to the 20 mm admixture. It is noted that long fibers lead to challenges during the mixing phase, resulting in agglomerations and significant defects in the microstructure of the cementitious system. Additionally, Fig. 9 highlights a consistent qualitative behavior as expected in every fiber-reinforced sample. Specifically, it is noted that after achieving the maximum flexural strength, there is a contained decay until the fibers are entirely involved in the flexural strength. This involves a limited hardening phase followed by a more contained decay, with a significant increase in the ductility of the samples.

Fig. 10 provides an overview of how varying fiber contents impact the flexural behavior of the ultralightweight foam concrete samples. The admixture 12mm-5 exhibits the most brittle behavior, reaching the maximum flexural strength within the first 0.5 mm. On the other hand, 12mm-10 admixtures reach the maximum flexural strength at around 2 mm, while 12mm-15 admixtures do so at around 5-7 mm. After attaining peak flexural strength, samples containing 5 kg/m³ of wool fibers display a residual flexural strength of 0.056 MPa. In contrast, the samples with 10 kg/m³ of wool fibers reach 0.427 MPa, while those with 15 kg/m³ fiber content reach a residual flexural strength of 0.791 MPa. The previous results show that the mixtures with fibers are more ductile than NF, given that the latter did not achieve a residual flexural strength range. The improvement between 12mm-5 and 12mm-10 was 123.06%, while the one between 12mm-10 and

12mm-15 was 20.14%. It is evident that higher fiber content results in a more ductile material; however, the highest content led to agglomerations during the mixing process, rendering it not ideal.

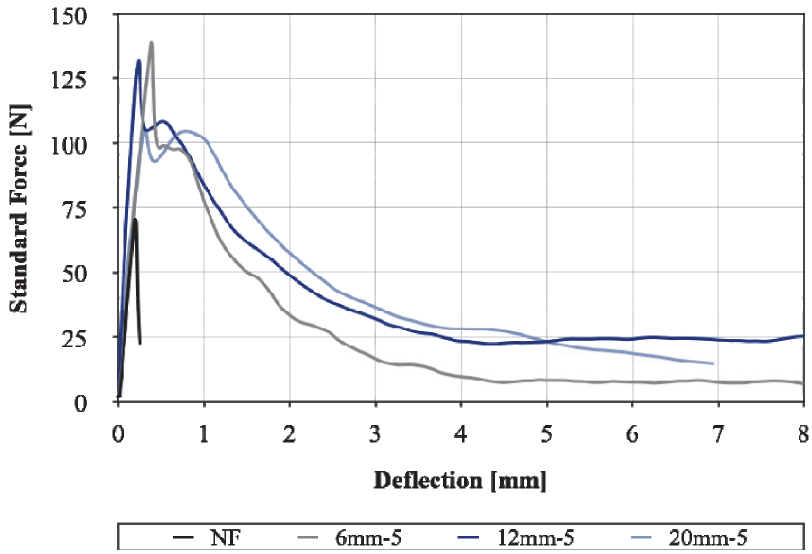

Figure 9: Effect of wool fiber length on the flexural behavior of ultralightweight foamed concrete.

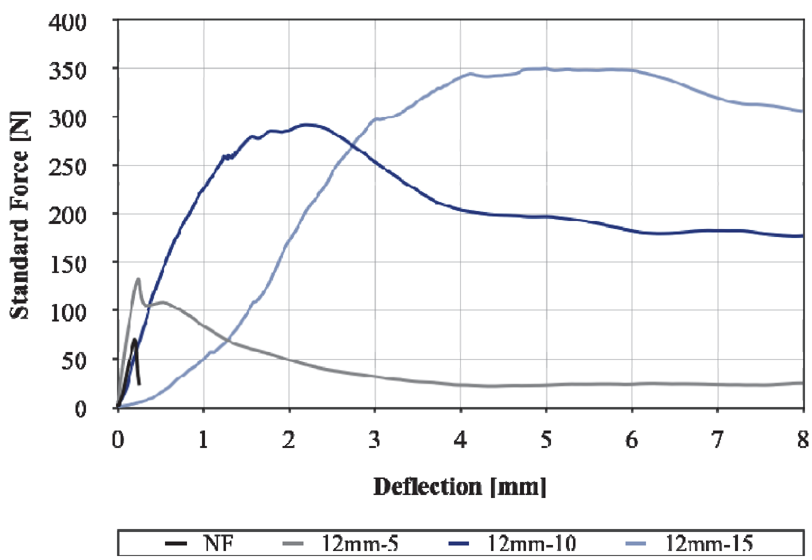

Figure 10: Effect of wool fiber content on the flexural behavior of ultralightweight foamed concrete.

Mechanical properties: compressive strength

The effect of fiber treatment on compressive strength values is reported in Fig. 11. The fibers treated with the foaming agent exhibited the highest average compressive strength, with a 44% improvement compared to those without fibers. They were followed by the mixes with fibers treated with salt and sodium hydroxide; the former presents a rise of 32% and the latter of 29%. LTF showed a 17% improvement compared to reference specimens (without fibers). In addition, NTF admixtures had the lowest compressive strength, decreasing by 11%. However, as for flexural strength, this could be ascribed to the fact that these specimens are characterized by the lowest density while falling within the acceptable range. Fig. 11 shows that as the density increases, so does the compressive strength, except for NaOHTF and NaClTF admixtures. Despite having a higher density than STF, these admixtures have a lower compressive performance, as previously noted for flexural strength. Consequently, these two types of fiber treatment were ruled out for future applications.

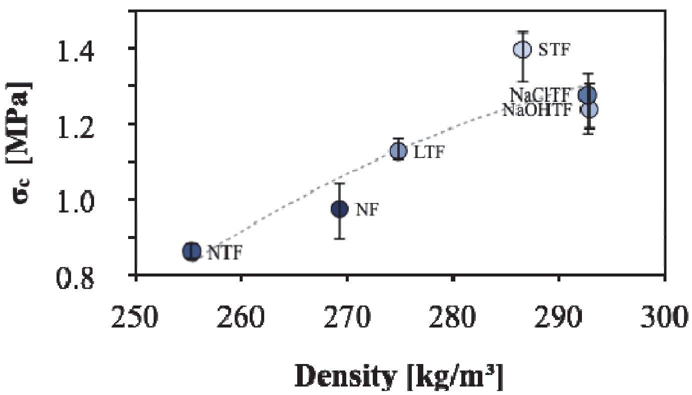

Figure 11: Effect of fiber treatment on compressive strength of foamed concrete with 5kg/m³ of 12mm fibers.

The impact of fiber length on compressive strength values is depicted in Fig. 12a. The study focused on a 5 kg/m³ fiber content. Specimens with 12 mm fibers exhibit compressive strength values that are 16% higher than those with 6 mm fibers. It was found that 12 mm is the optimal fiber length for enhancing the compressive strength of fiber-reinforced foamed concrete; in fact, a further increase in fiber length (20mm) resulted in a 9% lower compressive strength. The lowest compressive strength associated with the shorter fiber length could be explained by taking into account the fact that the presence of longer fibers could better bond the cement matrix lightened by the presence of air bubbles, creating a beneficial bridge effect that results in a sort of confinement which gives rise to an improvement in compressive strength.
Fig. 12b shows the highest compressive strength when the wool fiber content is 5 kg/m³. This can be attributed to fiber clumping at higher content levels (10-15 kg/m³), which leads to the formation of macro-voids and macro-defects. These voids and defects have a detrimental effect on the material's compressive strength.

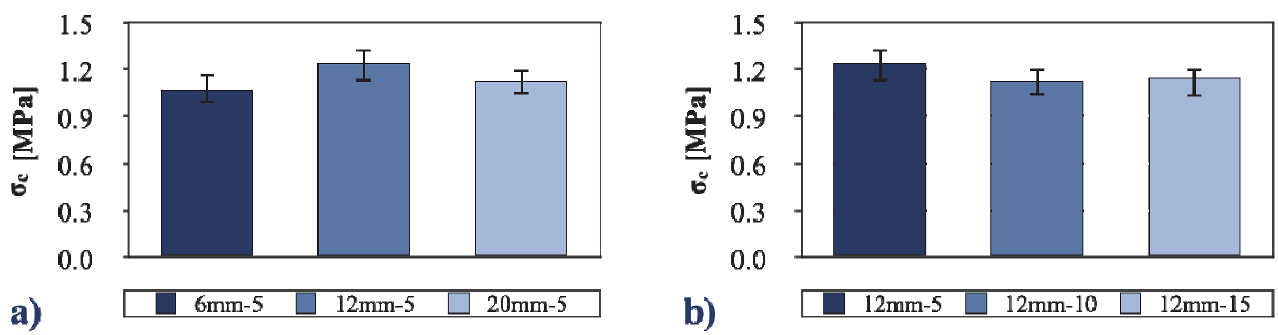

Figure 12: Effect of fiber length on compressive strength (a); effect of fiber content on compressive strength (b).

MAIN OBSERVATIONS

This research marks the beginning of a study on implementing SWF as a by-product in ultralightweight foamed concrete. It involves selecting the most advantageous fiber characteristics for further examination.
Regarding the fiber treatment, the most performant results for flexural and compressive strength are obtained by the STF mix with an increment of 61% and 44%, respectively. These results are potentially attributed to the positive impact of the surfactant treatment on wool fibers in enhancing the stability of the lightweight cementitious system. Furthermore, the surfactant molecules adhering to the wool fibers may contribute to achieving higher stability in the cementitious system during the mixing phases, potentially explaining the reduced amount of foam needed to reach the desired density in this scenario. In particular, a lower foam content implies a reduced water content, as foam is approximately 95% water. Given that lower water content is known to positively impact the mechanical properties of cementitious matrices, this factor may also have contributed to the observed increase in compressive strength. Consequently, this fiber treatment was selected for further analysis. Additionally, NaClTF and NaOHTF yielded the second-highest mechanical properties. However, although they are still within acceptable limits, their density values were

the highest. Therefore, these fiber treatments are considered below average when considering the relationship between density and mechanical performance. On the other hand, admixtures containing STF surpassed this trend, while NTF and LTF tend to be slightly above the trendline. Additionally, NaOHTF degraded during the treatment process, affecting the workability of the mix and its ductility. Therefore, these two types of treatment were not considered, suggesting that future studies should focus on STF, LTF, and NTF.

Regarding fiber length, samples with 6 and 12mm fibers have a 13% higher flexural strength than those with 20mm fibers. At the same time, 6mm fiber mixes had the most brittleness and the highest slump values. When considering compressive strength, the 12mm fibers exhibit the best performance; increasing the fiber length improves the compressive strength up to a certain point in which the size becomes excessive, causing fiber agglomerations and a decrement in compressive strength due to the heterogeneity of the cement matrix. Consequently, the 12 mm length is deemed optimal for wool fibers in foamed concrete. This length strikes a perfect balance between the necessity to bind and confine the cellular microstructure of the cementitious system and the increasing mixing challenges associated with longer fiber lengths.

Mixing problems, such as fiber agglomeration and the formation of defects like macro-voids in the microstructure, are emphasized with the highest fiber content studied, namely 15 kg/m³ of wool fiber. Consequently, this very high fiber content was deemed unsuitable. On the other hand, the mechanical properties exhibited different trends with 5 and 10 kg/m³ fiber content admixtures. The former performed better in terms of compressive strength, while the latter excelled in flexural strength. Hence, both will be considered in a forthcoming study to evaluate their impact on the material's properties under different densities, and their effect on the microstructure through the analysis of the pore size distribution and homogeneity under different conditions.

CONCLUSIONS

This study investigated ultralightweight foamed concrete reinforced with sheep wool fibers. The fresh and hardened state properties were evaluated, and the following main conclusions can be drawn.

- The incorporation of fibers in concrete admixtures significantly impacts the slump values and workability of the mixture. The study shows that the type of fiber treatment, fiber length, and fiber content all play crucial roles in determining the slump reduction and workability of the concrete. Longer fibers and higher fiber content lead to more substantial reductions in slump, but they also pose challenges such as agglomeration and reduced homogeneity during the mixing process. Therefore, it is essential to carefully consider the fiber treatment techniques, fiber length, and fiber content when designing concrete mixtures to achieve the desired properties without compromising workability.
- The incorporation of sheep wool fibers in producing ultralightweight foamed concrete significantly improves its flexural and compressive strength. Treating the fibers with the foaming agent improved their performance by up to 61% in flexural strength and 44% in compressive strength.
- Adding sheep wool fibers to ultralightweight foamed concrete increases the material's elasticity, which is generally very brittle. This could increase durability and reduce the development of cracks. These effects will be studied in a forthcoming paper, analyzing how these samples react after a more extended period.
- The optimal fiber content for ultralightweight foamed concrete is between 5 and 10 kg/m³. Higher fiber content levels led to fiber clumping, resulting in macro-voids and macro-defects, which negatively affected compressive strength.

In conclusion, this study demonstrates the potential for using wool fibers to create ultralightweight foamed concrete. After considering factors such as slump, brittleness, flexural, and compressive strength, it was determined that a fiber length of 12mm, STF treatment, and a content of 5 kg/m³ are the optimal parameters for performance. A forthcoming study in this area will explore the long-term durability and performance of ultralightweight foamed concrete reinforced with sheep wool fibers, as well as a microstructure analysis. Further research and development in this area could lead to the widespread adoption of sustainable and high-performance concrete materials.

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