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Research Article

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Potential Application of Flax Fibers in 3D Printed Cementitious Materials

Mengya Li[1], Said Rahal[1], Abdelhak Kaci[1*], Abdel-Okash Seibou[1,2] and Yunyun Tong[2]

[1]*CY Cergy Paris Université, L2MGC, Cergy, France*

[2]*Zhejiang University of Science and Technology, Hangzhou, China*

[*]Correspondence to:
Abdelhak Kaci
CY Cergy Paris Université,
L2MGC, Cergy, France.
E-mail: abdelhak.kaci@cyu.fr

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Abstract

Due to their low environmental impact and capacity to reduce carbon gas emissions, the incorporation of vegetal fibers in cementitious materials has been increasing. Besides, the building industry shows an upward trend in 3D printing technology due to their fast implementation, affordability, and ability to realize more sophisticated shapes at low cost. The stability of rheological criteria in relation to machine extrusion parameters is important when these composites manufactured by new construction techniques like 3D printing. This call to the understanding of the interaction in term of absorption capacity between the cement and vegetal fibers. In this work, two mixture preparation processes were used. Firstly, the mixture was prepared with dry flax fibers and extra pre-wetting water. However, increased yield stress over time was observed due to the high absorption capacity of dry flax fibers. Secondly, flax fibers were prewetted with a water amount close to their saturation point, 24 h before experiment, to prevent absorption from cement hydration. The morphology of composite was analysed by SEM (Scaning Electron Microscpe). In addition, the mechanical properties were assessed in the hardened state by compressive test and three-point bending test at different curing time. The results found that when the workability of the mixture remained within the desired range, the printing time had no effect the compressive and flexural strengths. The proportion of flax fibers added was insufficient to improve the ductility behaviour of the material.

Keywords

3D concrete printing, Bio-based material, Flax fiber, Mechanical behavior, Microstructure

Introduction

With the rapid development of economy generated by growth of Mondial population, the construction intensity continues to increase and the buildings are expected to be doubled by 2050 [1]. The digital fabrication has been developed in response for efficient and resilient construction. 3D concrete printing (3DCP), also known as additive manufacturing, is an automatic technology which generates cementitious layers by two techniques, extrusion or binder jetting. Compared with the traditional processes as mold-casting, 3D printed concrete presents advantages of no-formwork, freedom of design complex structures, as well as workers saving. 3DCP can be expected to save up to 60% construction wastes and 80% labor costs, even the delay can be reduced by 70% [2]. It is obvious that the automation and digitization will navigate the future of the construction industry.

The 3DCP usually consume large amounts of cement and nonrenewable resources. Previous research proved that the environmental impact of 3DCP could be higher than the conventional concrete due to the additional cement content

[3]. Many researches have been conducted on the ecological alternative solution of 3DCP, such as the replacement of natural aggregates by construction and demolition wastes. The investigation on the recycled aggregates, including glass, brick, sand and coarse aggregates have been carried on [4-7].

Bio-based cementitious materials, known as the sustainable concrete, have been highly studied due to their low carbon footprint and environmental benefits. The vegetal fibers are low-cost and renewable resources. However, few studies have been reported on the incorporation of natural fibers in the printed cementitious materials.

This study contributes to evaluate the potential of incorporating natural fibers in the 3DCP. The mix proportions and mixture preparations of flax concrete (FC) were assessed for acceptable printability. The rheological properties were characterized in order to attain the requirement of printing. The microstructure, as well as the physical and mechanical properties of printed FC were investigated.

Materials and Method

Materials

The flax fibers used in this study were provided by Briquetterie Dewulf (France). The fiber length was less than 20 mm and the skeleton density is about 1456 kg/m^3 (Figure 1). The fibers showed a water absorption capacity of 498 ± 14% with fast absorption kinetics. The binder used was ordinary Portland cement CEM I 52.5N, with a relative density of 3.18. The silica sand passing through a 2 mm sieve was used. The water-reducing superplasticizer was also applied to improve the printability and extrudability. Le et al. studied the relationship between using admixture in the mixture for 3DCP and open time [8]. The printability depends primarily on the rheological properties of mixture, while the adding of superplasticizer is more efficient than cement-water ratio. All used materials are nanoscale materials.

Specimens preparation

The FC specimens were prepared with two protocols. Protocol 1: The drying flax fibers were firstly mixed with cement and sand, then the prewetting water and mixing water were added to the mixture. The quantity of prewetting water was determined by the flax fiber water absorption rate and fixed at 4 times of the weight of fibers. Protocol 2: The flax fibers were pre-wetted for 24 h before mixture. After mixture of cement and sand, the wet flax fibers were added and continued to mix, the water were added at the last step. The mix proportion was 1:1:0.03:0.36:0.005 for cement:sand:flax fiber:water:superplasticizer, respectively. The specimens were designated as FC1 and FC2 for protocol 1 and 2, respectively. The same mixture was used to prepare the printed as well as cast specimens.

3D printing device and process

The printed specimens were printed by a gantry type printer BK3D (2 m x 2 m x 2 m) with 3 axes XYZ (Figure 2a). The large funnel of printer offers an extruded volume that exceed 1 m^3 and the output section of nozzle is 40 mm x 10 mm. The printing trajectories were piloted by a numerical file through a control box. The stepper motor and trapezoidal ball screws ensure the movement of nozzle with precision. The specimens were obtained by extrusion layer upon layer. Each layer has a thickness of 10 mm and a length of 400 mm. The layer was printed at a horizontal speed of 10 mm/s. The printed elements were used to cut two normalized specimens of 160 mm x 40 mm x 40 mm for experimental measurements.

Figure 1: Flax fibers.

Rheological properties

The rheological properties of FC were characterized by the slump test. The test was conducted with a mini cone apparatus (50 and 100 mm of diameter at the top and base, 150 mm of height). The measurement of workability was taken every 10 min over a period of 1 h. The fresh mixture was slightly stirred to ensure homogeneity.

Morphology

The morphology of printed FC in the hardened state was observed by a SEM. The samples were prepared beforehand with freeze-drying (lyophilizing) method.

Physical and mechanical properties

The physical and mechanical properties were characterized in the hardened state after 28 days. The density and porosity were measured by water impregnation. The mechanical properties were evaluated by three-point bending and compressive test on the prismatic and cubic specimens of 40 mm x 40 mm x 160 mm and 40 mm x 40 mm x 40 mm, respectively, according to EN 196 (Figure 3).

Results and Discussion

Rheological properties in the fresh state

Rheological studies are crucial for 3DCP. The mixture needs to be flowable enough to be extruded through printing nozzle, but also strengthen enough for buildability. The interaction of cement particles caused by the colloidal attractive forces results in the formation of a network of particles which are capable of resisting stress. The network is characterized by an initial elastic modulus and an initial yield stress. This ini-

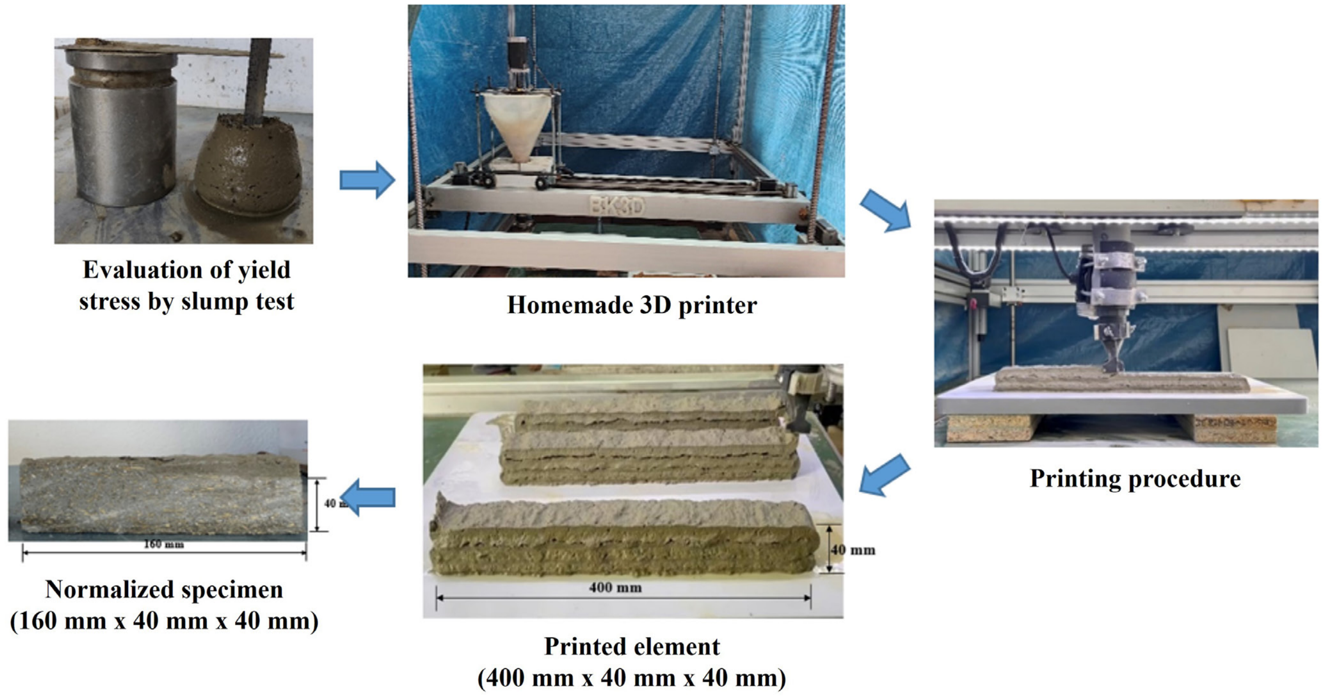

Figure 2: Illustration of 3DCP process.

tial yield stress must support the gravitational stress caused by layer-by-layer deposition process, primarily shear stress. This parameter can be evaluated using rheometers [9]. It can also be assessed by the slump test, slump flow test, V-funnel test or L-box test [10-12].

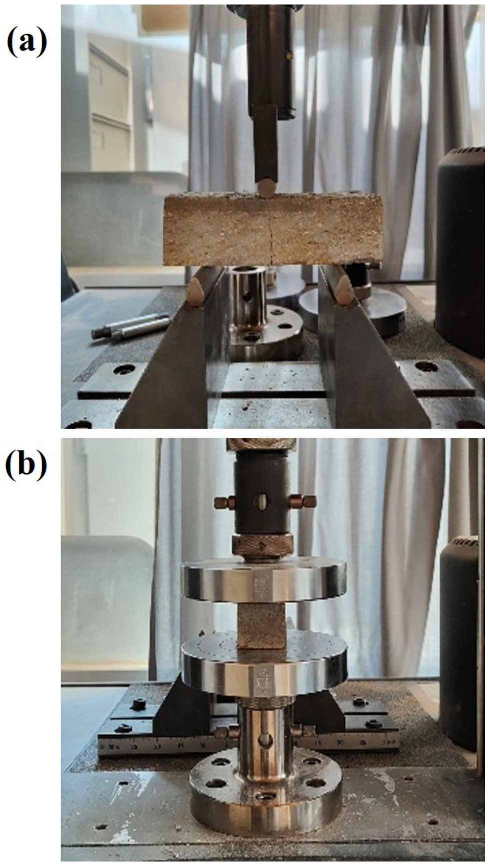

Figure 3: Mechanical properties measurement: **(a)** three-point bending test and **(b)** compressive test.

Accoridng to [13], the initial yield stress of any printed layer can be estimated using the following formula:

$$\tau_0 = \tilde{n}gH/\sqrt{3}$$

Where, ρ is the density of printed material, characterized as 1955 kg/m^3, g is the acceleration of gravity and h is the height of the printed layer.

Figure 4 displayed the evolution of slump value of FC in the fresh state over time. It can be observed that the initial yield stress of FC1 increased linearly with time. This can be attributed to the rapid absorption of water by the flax fibers, which resulted in extra water uptake from cement setting and a rapid increase in slump height. Another reason can be

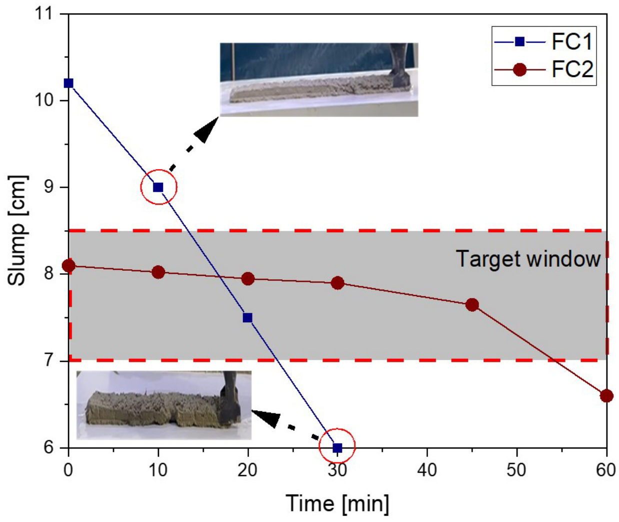

Figure 4: Evolution of slump height over time using mini MBE cone. FC1: the extrusion-based printability is ensured between 15 and 25 min. FC2: the extrusion-based printability is ensured between 0 and 55 min.

the high viscosity created by the vegetal fibers tangling [14], which surged the yield stress of mixture. Even though a low material yield stress was considered to be easier for extrusion, but also result in a loss of shape definition and stability, as observed at 10 min during the printing process of FC1. Meanwhile, a high yield stress can cause blockage during extrusion, as observed at 30 min during the printing process of FC1. The yield stress of FC2 was within the printable range until 55 min, which is in contrast to FC1. The difference can be attributed to the prewetting of the flax fibers for 24 h before mixing, which weakened or even eliminated their absorption capacity and thus had less effect on the cement setting process.

Morphology

The microstructure of FC specimens at 28 days were presented in figure 5. An incompatibility between natural fibers and cement matrix can be observed from figure 5a, while the anhydrite and cracks were both exposed. It has significate that the hydrate action of cement was not completed. The results were in accordance with slump test. The dry flax fibers continued to absorb the water from mixture, which leads to the decrease of workability of FC1. In addition, the FC2 exhibited a better interface. No anhydrite was found, and the bond between cement and flax fibers appeared to be improved.

Physical and mechanical properties in the hardened state

The density of cast and printed specimens was measured at 28 days of 160 mm x 40 mm x 40 mm normalized specimens by Archimedes method (buoyancy method) through immersion and the results were recapitulated in table 1. It should be noted that previous studies have highlighted the difficulties in accurately measuring of the density of vegetal fibers reinforced concrete [15]. The density measured by gas pycnometer was found 12% higher than that measured by water accessible method. It was recommended to evaluate density of flax fiber composite in air or fluid [16]. It can be noted that for two preparation process, both cast specimens were slightly low-weighted than printed specimens. The explanation could be the layer stacking increased the compactness and reduced porosity. Same reports were found in [17]. It can also be found the density of FC2 was higher than the FC1. The absorption of extra water from cement by flax fiber in FC1 may have result in an incomplete hydration and a weak bonding interface, leading to increased porosity of the matrix and reduced density.

Table 1: Density of cast and printed FC.

Parameter	FC1		FC2	
	Cast	Printed	Cast	Printed
Density [kg/m^3]	1927 ± 27	1936 ± 31	1977 ± 28	1996 ± 3.9

The mechanical properties were evaluated by flexural and compressive strength. The investigation was first carried out into the relationship between the slump value and mechanical strength of FC1 at 28 days. The experimental results were presented in figure 6. It was observed that the slump loss had few effects on the mechanical strength within the printable

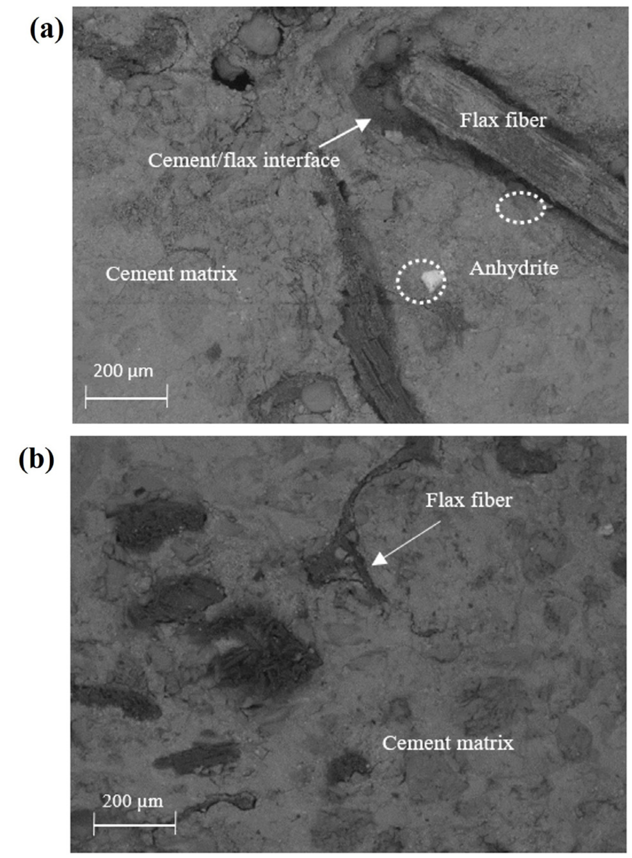

Figure 5: SEM observation of **(a)** FC1 and **(b)** FC2 at 28 days.

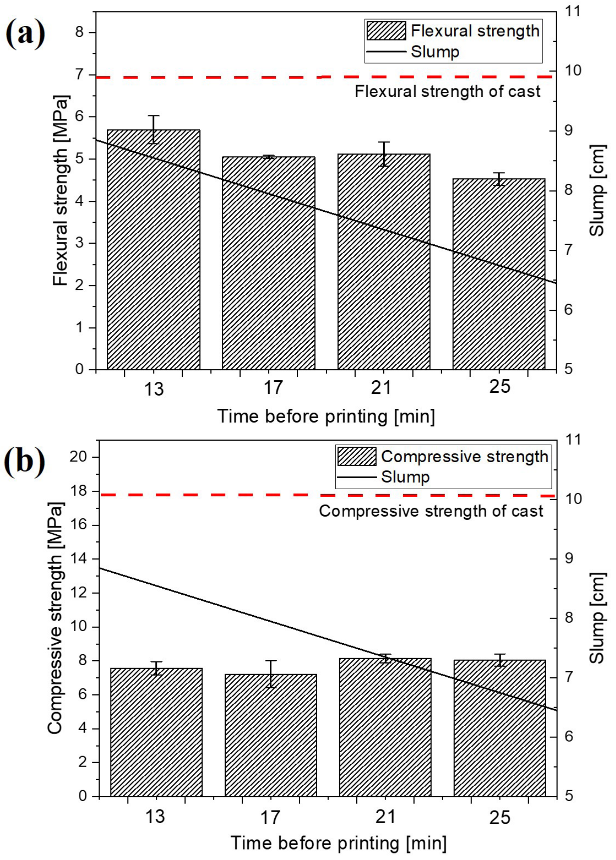

Figure 6: Evolution of mechanical properties of printed FC1 at 28 days: **(a)** flexural strength and **(b)** compressive strength.

range. However, the specimens printed at 25 min showed a 7% decrease in flexural strength. This was deemed unsatisfactory for printing with firm consistency. On the other hand, a decrease of 24% bending strength was found between cast and printed specimens. The printing time and the workability had limited impact on the compressive strength, while the values printed at different times were very close to around 7.8 MPa. The cast specimens showed a better compressive strength at 18 MPa.

As indicated by the initial yield stress, FC2 had a more stable rheological properties, while the initial yield stress remained in the acceptable range until 55 min. The effect of workability and printing time on the mechanical properties can be neglected. Therefore, the bending and compressive strength were evaluated by the curing time at 3, 7, 14, and 28 days. The experimental results of three-point bending were depicted in figure 7. The specimens exhibited a linear behavior before reaching the peak load (Figure 7a). While the addition of fibers was generally expected to enhance the ductility of cementitious material, in this study a brittle failure was observed after the peak load, indicating a lack of ductility. This result suggested that increasing the proportion of flax fibers in the mixture is expected. The flexural strength of printed specimens increased over curing time (Figure 7b). It can be attributed to the gradual hardening of cement and the development of stronger bonds between cement and fibers. Besides, the bending strength of printed specimens was 5.9% higher than cast specimens at 28 days. The explanation of this increase can be the interlayer bonding. Murcia et al. [18] reported that the extrusion process can promote the compaction of 3DCP, which also improves its mechanical behavior. Another reason could be the alignment of majority fibers along extrusion direction, which enhanced the flexural strength. Similar results have been reported in 3DCP incorporated PVA fibers [19].

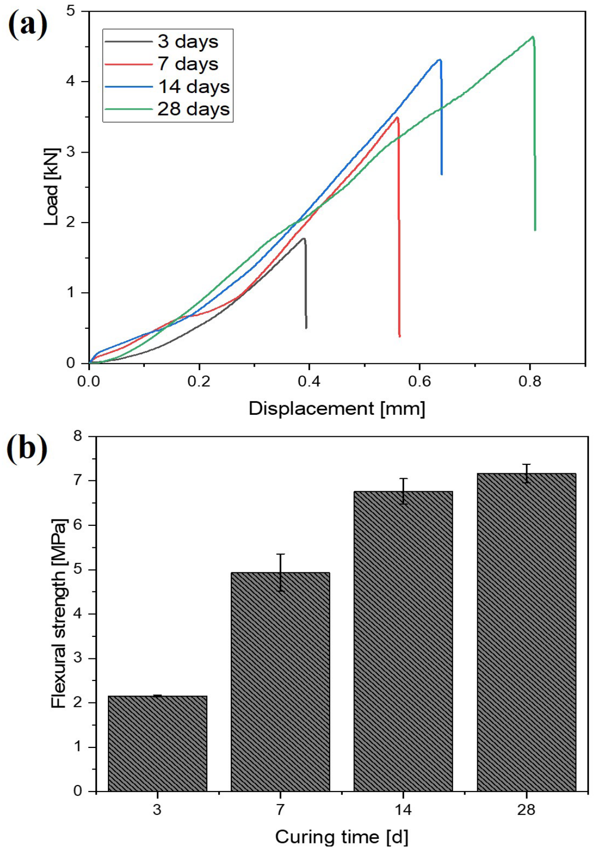

Figure 7: **(a)** Load-displacement curves of printed specimens and **(b)** evolution of flexural strength of different curing time.

The load-displacement curve in figure 8a showed a non-smooth curve, indicating the slippage during the tests. This could be attributed to the quality of specimen's surface. The compressive strength of printed specimens over curing time was depicted in figure 8b. The result showed a rapid increase in compressive strength during the first 7 days and then slowed down at 14 and 28 days. After 7 days of curing, the compressive strength had reached 76% of the value at 28 days.

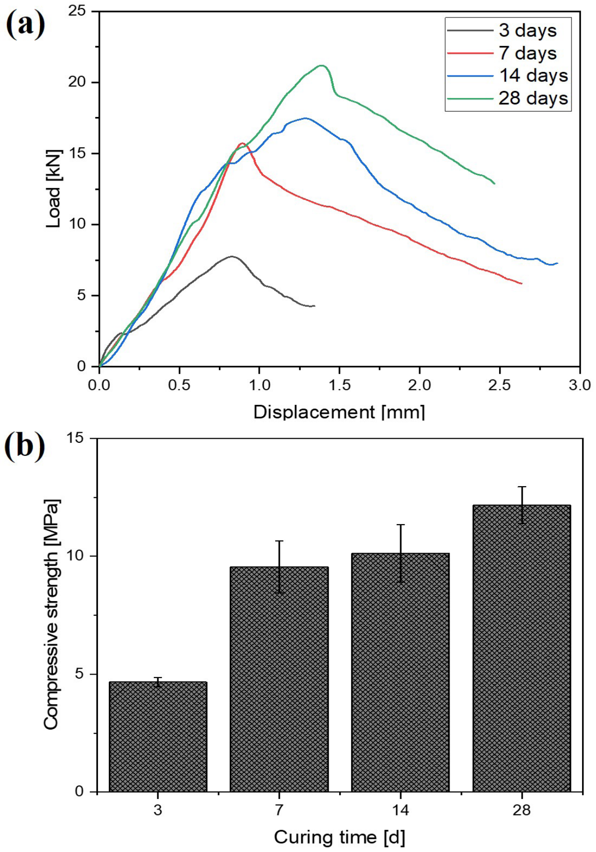

Figure 8: **(a)** Load-displacement curves of printed specimens and **(b)** evolution of compressive strength of different curing time.

Conclusion

In this study, the potential of incorporating flax fibers into printed concrete was investigated. Two preparation processes, using dried and prewetted flax fibers, were utilized to develop a new bio-based concrete. The mix proportion of the FC was designed based on their rheological properties. The cast specimens were slightly lower-weighted than printed specimens. The printing time had a minimal effect on the mechanical properties when the slump remained within the desired range. The concrete prepared with prewetted flax fibers exhibited a better bonding interface between the fibers and cement matrix, resulting in improved mechanical properties compared to specimens prepared with dried fibers. The proportion of flax fibers incorporated was insufficient to improve the ductility of material.

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None.

Conflict of Interest

Authors declare no conflict of interest.

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