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Viability of flax particles to develop cellular construction materials: Physico-mechanical characterisation

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Abstract. The problems related to environmental issues have motivated extensive research on environmentally friendly materials. The built environment is responsible for high primary energy use and more of energy related CO_2 emissions. However, it is important to develop low-embodied energy, carbon-negative, sustainable construction materials to replace conventional products. In this context, agricultural wastes are the excellent alternative materials to substitute mineral aggregates because they are widespread and easily accessible. The application of these elements is interesting as regards the recycling of the vegetable particles, since these are easily available and renewable low-cost raw materials, and has advantage for economy and environment. However, the reduction of energy consumption in construction, production of thermal insulation materials, and the solution of environmental problems by recycling waste are becoming greater problems. Various types of agriculture waste, after being processed, have been used as particles in concrete or mortars. These materials display lower density and have several potential applications such as acoustic and thermal insulation, fire resistance cladding…etc.
The study reported in this paper was undertaken to investigate the physico-mechanical properties of cellular materials based on flax particles, in order to produce usable materials in cellular concrete applications. The material produced containing different volumes of flax particles (0V (control mortar), 1V, and 2V) was lightened by creating a porous structure in the matrix through a chemical reaction between aluminium powder and free lime. A study conducted on hardened material properties has indicated a significant reduction in sample unit weight, thereby resulting in a level of compressive strength compatible with a load-bearing wall. The reduction in flexural strength was lower than that in compressive strength. These results shown that the cellular material based on flax particles can be used as suitable insulated load-bearing walls.

Key words: Flax particles, Cellular Concrete, Feasibility, Porous Structure, Physico-Mechanical Properties.

1. Introduction

Wastes from different sources are causing environmental problems associated with their storage and their rising quantities (Europäische Kommission, 2014). In the construction field, the recycling of agricultural wastes is increasingly considered. The needs to conserve traditional building materials that are facing depletion have obliged engineers to consider alternative materials. However, the use of renewable raw material derived from agricultural products has been the subject of extensive research, while different types of agricultural wastes including hemp, flax, rapeseed, jute, palm… have been used as particles and/or fibres replacement of sand and aggregates in concrete and mortars (Islam and Ahmed, 2019; Benmahiddine et *al*., 2020; Al-Kutti et *al*., 2018). The application of these elements is interesting as regards the recycling of the wastes, since these are easily available and renewable low-cost raw materials, and has advantage for economy and environment.

The versatility of using vegetable materials in concrete to replace mineral aggregates has given rise to several applications in lightweight construction field. According to the literature, extensive studies have shown the benefits of hemp particles reinforced materials, as non-load bearing construction materials, while the influence of different parameters including particle sizes, hydraulic and/or organic binder type, and casting process have been reported. The results have promoted several interesting properties of specimen such as a low density, acoustic and thermal insulation, fire resistance, and higher hygro-thermal performances (Ingrao et *al*., 2015; Arnaud and Gourlay, 2012; Evrard and De Herde, 2009; Le et *al*., 2015). In addition, the hemp particles reinforced concrete offers a high-quality living environment due capability to regulate indoor humidity of buildings by absorbing and/or releasing water (Mazhoud et *al*., 2021, Benmahiddine et *al*., 2020; De Bruijn and Johansson, 2013; Asli et *al*., 2021). The panels based on hemp hurds with novel hybrid organic-inorganic binders characterized by their physical, microstructural, thermal, and mechanical properties have shown parameters comparable to those of commercially available products (Santos et *al*., 2015; Manzi et *al*., 2013). Although the demand for vegetable materials is growing worldwide, the specimen-based these plants need further research with respect to the opportunities for their use, and to provide novel products with improved properties. Another more innovative way consists to develop new cellular construction materials based on flax particles, in order to produce usable specimen in cellular concrete applications. Through appropriate production methods, cellular concrete featuring a wide range of densities (300–1800 kg/m^3) may be obtained, in comparison with 2300 kg/m^3 in density for traditional concrete (Panesar, 2013). A further innovative strategy is the lightened of the materials by creating a porous structure in the matrix through a chemical reaction between Aluminum powder and free lime contained in hydraulic binder. According to the researches down, these materials remain relatively unexplored.

The scope of this study is to investigate the potential use of flax particles in preformulated Tradical PF70 hydraulic based-binder, within the scope of providing usable specimen in cellular concrete applications. The influence of flax particles volume (0V (Cellular Control Specimen), 1V, and 2V) on the physic-mechanical and thermal properties has been evaluated.

2. Materials and experimental testing

2.1. Materials and specimen production

The vegetable particles used in this study are waste by-products materials derived from linen industry. Resulting from flax fibres stripping process, these materials contain a mixture of flax particles, steam fragments, lint, and wood shaves. The shape and properties of flax particles used in this study are shown in Fig. 1 and Table 1, respectively.

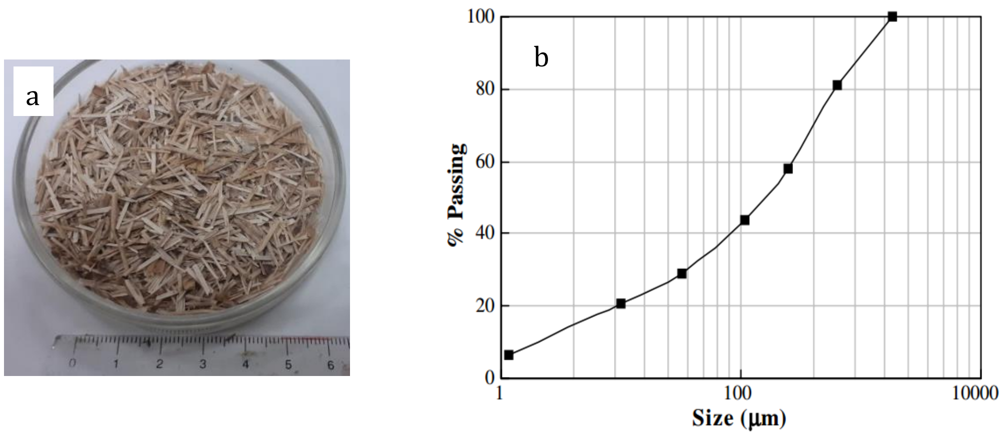

Fig. 1. Shape (a) and particle size distribution (b) of flax particles

Table 1. Properties of flax particles

Bulk density (kg/m^3)	Absolute density (kg/m^3)	Porosity (%)	Water absorption (%)
100	1054	90.5	280

The preformulated lime binder used in this study, called "Tradical PF70" is supplied by "LHoist" industry, of the Northern region of France (BCB, 2015). It contains 75% air lime, 10% hydraulic lime, and15% of pozzolan mixture, where the binder is already used to produce hemp concrete. The use of this binder has several advantages that are related to its hydrophobic nature which acts as protective barrier for included vegetable particles when specimen exposed to hygroscopic environment.

Constituent materials mixes included Aluminum powder with 325 mesh in size and 99% purity, used for the lightening process, and flax particles added at different volume of 0 (Control Specimen), 1, and 2. The used amount of Aluminum powder in mixes is 0.3% by weight of binder.

Both Tradical PF70 binder and Aluminum powder were initially mixed in a planetary mixer. After water adding, flax particles were uniformly dispersed with slow increment throughout the binder. The fresh materials were allowed to mix for three additional minutes. All the specimens were then cast on a vibrating table and moist-cured for 28 days at 20 ± 2 °C and 98 % relative humidity. For hardened properties measurement, prismatic (40 x 40 x 160 mm) and cylindrical (110 x 220 mm) samples were prepared for flexural and compressive-tests, respectively. The expanded volume of fresh specimen after casting due to the chemical reaction between Aluminum powder and free lime contained in binder is shown in Fig. 2, while the chemical reaction occurred produces hydrogen gas in the binder, and thus creates microscopic air bubbles in the matrix, according the chemical reaction mechanism illustrated bellow. After 24h and before demoulding, the expanded parts of the hardened samples were cut. The corresponding composition-mixes and designations of samples are summarized in Table 2.

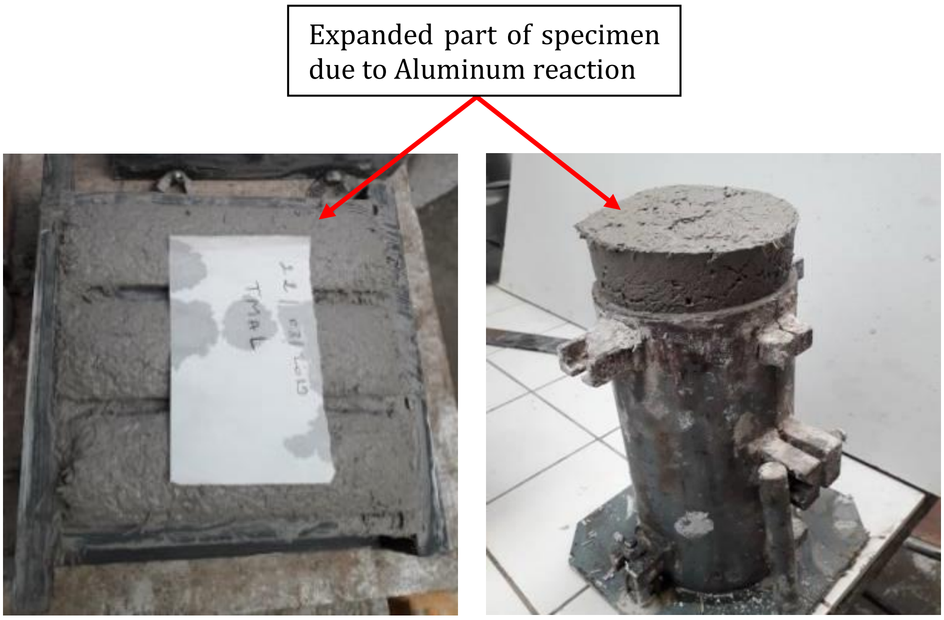

Fig. 2. Shape of fresh specimens

$$2Al + 3Ca(OH)_2 + 6H_2O \rightarrow 3CaO.Al_2O_3.6H_2O + 3H_2$$

Aluminum powder + Calcium Hydroxide Tricalcium Hydrate + hydrogen

Table 2. Composition-mix and I.D of specimens

Specimen-ID	Tradical binder (kg/m^3)	Flax particles (kg/m^3)	Alum./Binder ratio by mass (%)	Water/Binder ratio (by mass)
CS[a]	528	0	0.8	0.50
MF1[b]	287	39.85	0.8	0.65
MF2[c]	199	55.34	0.8	0.80

[a] Control Specimen ; [b] Specimen with 1 Volume flax ; [C] Specimen with 2 Volumes flax

2.2. Experimental testing

After 28 days of curing time, the dry bulk density was measured, after oven-drying the samples at 70 ± 2 °C, by means geometrical measurement and weighting. The apparent open porosity measurement was performed using the vacuum saturation method (ASTM C20–00, 2019). A dry sample of 40 x 40 x 40 mm in dimensions was placed in a desiccator and air was evacuated during several hours, using a vacuum pump and then water was injected until total immersion of the sample. As the material reached constant weight, the open porosity can be deduced from three mass measurements: dry mass and saturated mass obtained by weighing in air and saturated mass obtained by hydrostatic weighing.
The mechanical properties were evaluated by performing compressive and flexural tests, in accordance with European Standard NF EN 196-1 (AFNOR, 1995), using an electromechanical testing machine TINUS OLSEN H50KS model, equipped with a load cell of 50 kN (Fig. 3). The rates of compressive and flexural loading were 4 mm/min and 0.4 mm/min, respectively. Three replications were used for each property tested. The compressive stress-strain and the flexural load-deflection diagrams were recorded to evaluate several mechanical parameters of specimens.

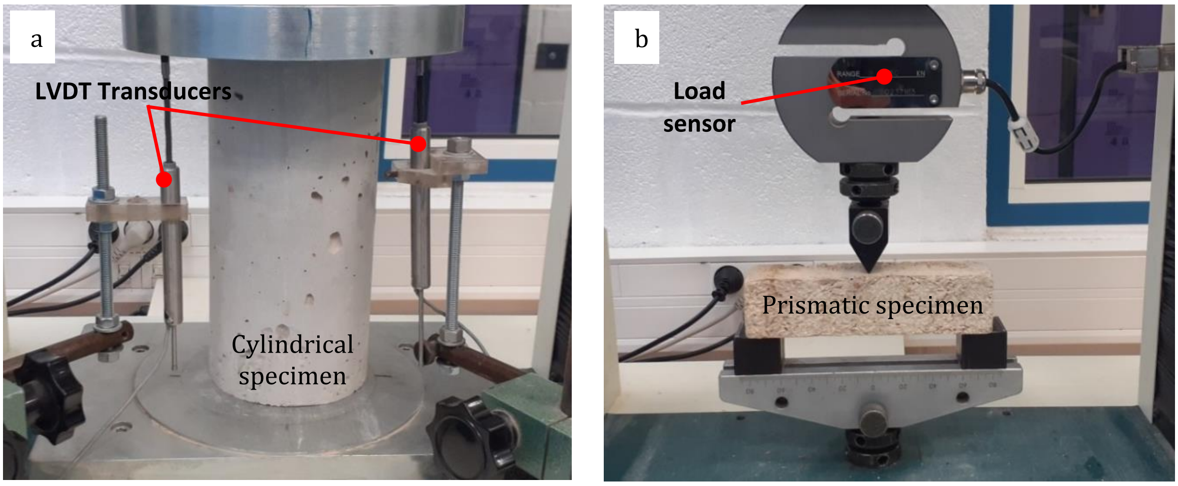

Fig. 3. Mechanical-test machines. (a): Compressive-test ; (b): Flexural-test

3. Results and discussion

3.1. Specimen lightening

The effect of change in flax particles volume on dry unit weight of the specimen is shown in Fig. 4, while the value decreased from 1080 kg/m^3, for control specimen (0 volume of flax), to 590 kg/m^3 for specimen with 2 volumes of flax particles. These values correspond to reduction of up to 44%. The decrease in unit weight is due to the physical properties of flax, since it has low density. In addition, the reaction between Aluminum powder and free lime creates porous structure that lightened the samples. Fig. 5 shows the air void structures of control specimen compared to the specimen-mix with 2 volumes of flax particles, while uniform air voids distribution and continuous cells were observed in all specimen mixes. As reported in Table 3, the total porosity-values, measured by vacuum saturation, indicated that the increase of flax particles increases porosity of specimen. The corresponding value varied from 28 % to 69 %. This contributes to lightening the material which make in the same magnitude of traditional cellular concrete in term of density ranged from 300 to 1800 kg/m^3.

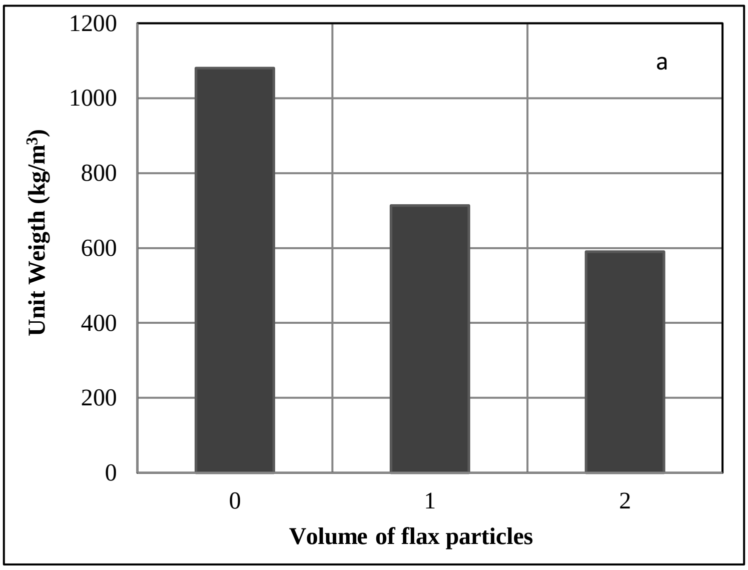

Fig. 4. Variation of dry unit weight vs. Flax volume

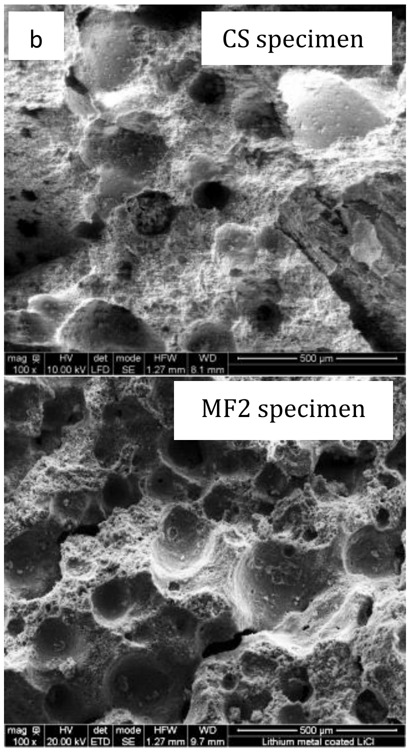

Fig. 5. SEM micrographs of specimen microstructure

Table 3. Physical properties of specimens

Specimen-ID	Bulk density (kg/m^3)	Open porosity (%)
CS	1080 ± 20	28 ± 5
MF1	713 ± 25	63 ± 10
MF2	590 ± 35	69 ± 12

3.2. Compressive strength of specimens

The 28-days stress-strain diagram of specimens with respect to the flax particle content is presented in Fig. 6. The results indicated that the increase of flax particles volume serves to reduce compressive strength. Value decreases from 1.52 MPa, for Control Specimen, to 0.74 MPa for specimen containing 2 volumes of flax (MF2). It corresponds to reduction of approximately 53 %. The decrease in compressive strength is related to the mechanical properties of flax materials since they are less stiff than the surrounding hydraulic binder paste. The low strength of flax may be the important limiting factor affecting the specimen mechanical properties that leads to interfacial bond defects between particles and matrix. The decrease in compressive strength is also related to porous structure of sample. The more the air-bubble ratio, the lighter the specimen and the lower its mechanical strengths. The 28-days parameter-values of specimens, subjected to compressive test, are shown in Table 4. The corresponding elastic modulus-value varied from 353 to 212.5 MPa for MF2 specimen. The results highlight the ductile failure of the specimen-based flax particles that exhibits high plastic phase and underwent significant displacement before fracture. The variation of ultimate strain-value from 6.95 mm/m to 12.55 mm/m, showed that the addition of flax particles allows to make the specimen more ductile, as regards the elastic behaviour.

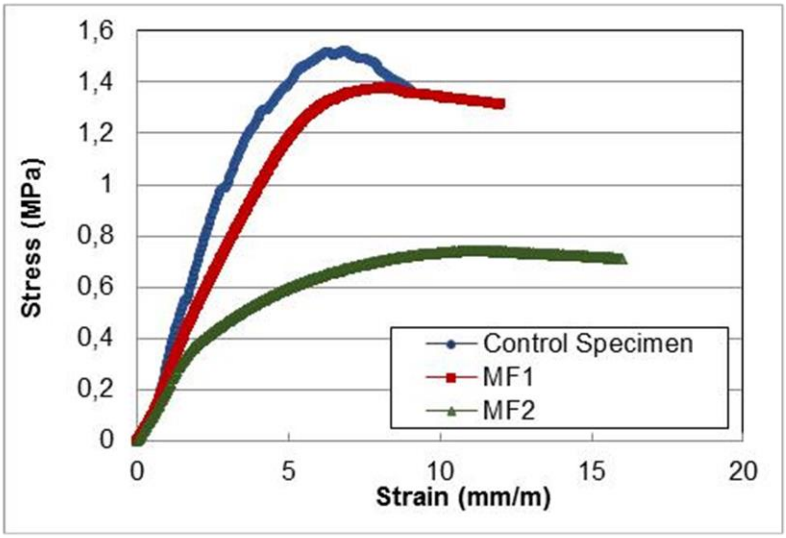

Fig. 6. Stress-Strain diagram of specimens under compressive test

Table 4. 28-days parameter-values of specimens under compressive test

Specimen-ID	Compressive Strength (MPa)	Ultimate strain (mm/m)	Elastic modulus (MPa)
CS	1.52 ± 0.10	6.95 ± 0.52	353.0 ± 25
MF1	1.38 ± 0.15	8.18 ± 0.95	242.4 ± 44
MF2	0.74 ± 0.18	12.55 ± 1.14	212.5 ± 53

3.3. Flexural strength of specimens

The 28-days load-deflection curves in flexural behaviour with different flax volume is shown in Fig. 7. A low reduction in the flexural strength of the specimen is observed with particles adding. Value decreases from 1.18 MPa, for reference specimen, to 1.05 MPa for MF2 sample with 2 volumes of flax. The value corresponds to reduction of up to approximately 11 %. This finding suggests that both mechanical properties of particles and sample's porous structure decrease the mechanical strengths of specimen. Results also indicated that for a given flax ratio, the decrease in flexural strength is lower than that in compressive strength, probably due to the dilution effect of flax particles.

It is considered that the tension effect of the flax particles occurs during the diffuse micro-cracking phase of "bending" the active micro-cracks and then in delaying the onset of their appearance, which serves to improve material flexibility. This could be also explained by the capability of flax particles to bridge the cracks and lead to limit their progression in the matrix. This bridge effect makes ductile material. The corresponding parameters, indicated in Table 5, show an increase in deflection with flax particles addition from 0.20 to 1.29 mm with 2 volume of flax addition. The variation of elastic modulus confirms this tendency with decreasing the corresponding value from 331.70 to 78.56 MPa, thus showing a ductile behavior of specimen containing flax particle, as compared to that without flax which in contrast exhibited a brittle failure.

Fig. 8, which compares the shapes of specimens after failure, highlighted the bridging effect of flax particles thus allowing to control the rate of cracks propagation. In contrast to the control specimen which exhibited a sudden fracture followed by fast crack propagation, the addition of flax particles allowed the sample to fail progressively and to maintain its structure due to the bridging effect of flax particles.

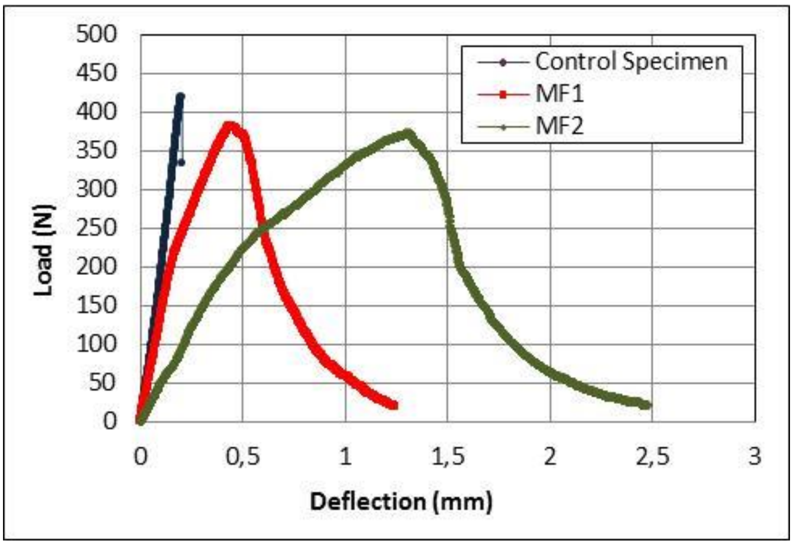

Fig. 7. Load-Deflection diagram of specimens under flexural test

Table 5. 28-days parameter-values of specimens under flexural test

Specimen-ID	Flexural strength (MPa)	Ultimate deflection (mm)	Elastic modulus (MPa)
CS	1.18 ± 0.03	0.20 ± 0.05	331.70 ± 25
MF1	1.07 ± 0.05	0.43 ± 0.08	222.89 ± 35
MF2	1.05 ± 0.07	1.29 ± 0.10	78.56 ± 18

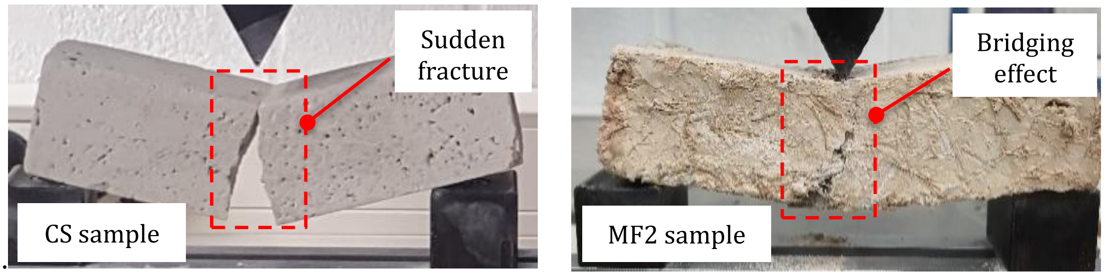

Fig. 8. Shapes of specimens after flexural failure

4. Conclusions

A test program was conducted in this study to develop information about properties of cellular specimen based on flax particles. The test results indicated that there is great potential for the use of flax by-product in binder mixes to produce usable lightweight construction materials in cellular concrete applications, such as load-bearing wall materials. Tests-result, performed on hardened specimen, have shown that the sample reached a dry unit weight of about 590 kg/m^3 with a compressive strength of 0.74 MPa. The reduction is related to both low stiffness of particles and porous structure of the specimen. The decrease in flexural strength is lower than that in compressive strength due to the bridging effect of flax particle. This research highlighted the effect of adding flax particles to attain substantial properties of innovative cellular materials and allows considering a broad range of applications in the field of cellular concrete. In spite of the positive implications of the test-results, supplementary research is required to examine the effect of varying porous structure level on physico-mechanical and thermal properties of the materials.

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