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Hempcrete – CO_2 Neutral Wall Solutions for 3D Printing

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Abstract **– Hempcrete is a bio-based self-bearing envelope and thermal insulation building material that is becoming more popular nowadays and has a low environmental impact, especially CO_2 emissions. This study looks for solutions for hempcrete printing using a custom-built gantry type 3D printer typically used for concrete 3D printing. Preliminary research shows that hempcrete can be printed at a relatively low density of 660 kg/m^3 and achieve an adequate buildability and compressive strength for printing individual wall elements. At this density, hempcrete has a thermal conductivity of 0.133 W/(m·K), unable to provide the adequate thermal resistance at average wall thickness, so high-density hempcrete should be printed as an outer wall shell (similar to Contour Crafting) and the middle filled with lower density thermal insulation hempcrete. By calculating the CO_2 emissions of such printed 400–620 mm thick walls, it was found that they absorb from 1.21 to 16.7 kg of CO_2 per m^2, thus, such material could reduce the negative environmental impact of the construction industry while improving its productivity through 3D printing.**

Keywords **– Bio-based materials; ecological materials; environmental impact; hemp; lime; life cycle assessment (LCA)**

Nomenclature		
GWP	Global warming potential	kg of CO_2 eq.
λ	Thermal conductivity	W/(m·K)
U	Thermal transmittance	W/(m^2·K)
RH	Relative humidity	%
MBV	Moisture buffering value	–

1. INTRODUCTION

The European Union's (EU) Energy and Climate Framework for 2030 [1] and EU climate law [2] set out sustainability requirements for customers and regulators, and the European Green Deal sets out these requirements to be net-zero greenhouse gas (GHG) emissions by 2050 [3]. The construction sector is responsible for more than 35 % of the EU's total waste and greenhouse gas (GHG) emissions, as reported in the Circular Economy Action Plan [4].

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The European Green Deal emphasizes the need for energy-intensive industries to decarbonize [5], therefore, the construction and building materials sector needs to become more sustainable, as natural resources are declining and total global CO_2 emissions are only rising. Therefore, alternative and resource-saving construction methods and raw materials are needed to produce construction materials.

One of the ways to do this is to increase the role of renewable natural resources in the production of building materials and structures and to emphasise low-energy, environmentally friendly structures by replacing non-renewable natural resources with renewables [6]. By using agricultural by-products or waste as raw materials, it is possible to achieve high CO_2 uptake and storage, as each season, the crops grow and store carbon in the process, consuming CO_2, thus sequestering it from the atmosphere [7]. Using these by-products or waste as raw materials in such long-lasting materials as building materials make it possible to lock in CO_2 into these materials for many years to come.

Hempcrete is a bio-based building material that is becoming more popular nowadays and is made up of lime-based binder and bio-based filler – hemp shives, an agricultural by-product resulting from hemp fibre processing. It is used as a self-bearing envelope and thermal insulation material and has a low environmental impact [8], especially CO_2 emissions, as they have been sequestered during the growth of the hemp plants [9]. Additional CO_2 is also absorbed during the hardening of the lime binder, as it hardens by carbonation, absorbing part of the CO_2 emitted during the production process and thus reducing total emissions [10]. The hygrothermal properties of hempcrete provide both indoor comfort and good thermal performance, which is also important in assessing the sustainability of the material. Hemp concrete offers low thermal conductivity from 0.06 to 0.13 W/(m·K), high vapour permeability ~ 10–11 – 10–10 kg/(m·s·Pa) and good moisture buffering with moisture buffering value (MBV) > 2 [11].

Several studies have been conducted that have looked at the environmental impact of hempcrete and other hemp-based materials, paying special attention to GHG emissions. Comparisons have also been made with traditional wall constructions with similar U-values. Arrigoni *et al.* [10] studied hempcrete blocks and the GHG balance of their production and obtained –12.09 kg of CO_2 eq. per m^2 of 250 mm thick wall. The study also concluded that the main impact comes from binder production, block production generates only 2 % of total emissions. Pretot *et al.* [12] investigated the effect of thickness on sprayed hempcrete walls and obtained –1.6 kg of CO_2 eq. per m^2. Also, this study concluded that the application of the material causes insignificant emissions compared to binder production. In a study comparing different traditional and innovative wall types, Sahmenko *et al.* [13] proves that walls with a U-value of 0.18 W/(m^2·K), built from traditionally used materials, such as uninsulated autoclaved aerated concrete blocks or insulated reinforced sandwich structures emit from 82.8 to 95.5 kg of CO_2 eq. per m^2. However, walls built using bio-based filler and various mineral binders, such as lime and magnesium oxychloride cement, can absorb from 9.5 to 30.91 kg of CO_2 eq. per m^2.

Another way to create sustainable building materials is to use more efficient production methods that reduce both the consumption of materials and the amount of waste generated. 3D printing of concrete and other building materials is a new construction technology that can reduce the consumption of building materials and waste, as printing allows optimizing the model before printing, so only the minimum amount of material is needed for the final print [14], as well as construction without scaffolding which significantly reduces the environmental impact [15]. It also reduces the need for low-skilled labour by improving the construction industry's productivity through automation. In addition, it gives much more freedom in the form of structures, as there is no need to use formwork. The use of 3D printing in the construction industry is evolving rapidly, and in a few years, it has evolved from prototyping to fully printed homes [16].

By using bio-based materials in combination with 3D printing technology, it would be possible to create more sustainable products for the construction industry while simultaneously improving its productivity [17]. Therefore, this study is looking for solutions for hempcrete printing using a custom-built gantry-type 3D printer typically used for concrete 3D printing. To determine the suitability of hempcrete for 3D printing, the buildability, green strength, and mechanical properties were determined of the hempcrete mixture with a minimum amount of binder. In addition, the possible use of hempcrete with the following properties was identified, and a life cycle assessment was performed to assess whether adding an additional binder did not have an excessive environmental impact. Differences in printed and cast hempcrete properties were identified to facilitate manufacturing methods for further composition studies.

2. MATERIALS AND METHODS

2.1. Materials and Mixtures

Hempcrete is made of lime-based binder and hemp shives. Lime-based binder used in this research is hydrated lime *Natura CL90 S* produced by Lhoist Poland Ltd. Used hemp shives are grown and processed in Lithuania (Naturalus Plostas). The granulometric composition of hemp shives is as follows – 72.5 % of shives by weight being in the range of 1–20 mm, 20.5 % in the range of 20–40 mm, and the rest being dust, fibre, seeds, and leaves. The bulk density of hemp shives used is 80 kg/m^3, the compacted bulk density is 110 kg/m^3, and the bulk form thermal conductivity λ is 0.043 W/(m·K). Maximum water absorption is 456 % at 48 h immersion, 325 % at 1 h immersion.

The composition for approximately 32 L of a fresh mixture is shown in Table 1. It is a variation of the compositions previously used, aiming to achieve a density of 600–700 kg/m^3 using a hemp:lime ratio of 1:10, giving the best print at the lowest density. The amount of water for lime is in a ratio of 7:10 to the weight of lime. The amount of water for hemp is 1:2 by weight of hemp due to the high-water absorption of the hemp shives so that the water needed to ensure the flowability of the mixture is not absorbed too quickly.

TABLE 1. HEMPCRETE MIX PROPORTIONS

Hemp shives, kg	**Lime, kg**	**H_2O for shives, kg**	**H_2O for lime, kg**	**H_2O/ lime**	**Hemp shives/lime**	**Hemp shives/H_2O**
2.0	20.0	4.0	14.0	7:10	1:10	1:2

2.2. Mixing, 3D Printing, Casting and Curing

Initially, the hemp was mixed with water in a ratio of 1:2, mixed by hand to pre-wet the hemp shives. Tap water with a temperature of 9.5 °C was used. The mortar and composite were mixed using a *Rubimix-9 N* electric mixer at 780 RPM. The lime was mixed with water for 1.5 min, after which pre-wetted hemp was added and further mixed for 1.5 min.

3D printing was performed with a gantry type printer with a batch type printhead, the printer was used in previous studies on the printing of bio-based materials [18]. Print speed – variable, on average 33 mm/sec. A 38 mm round nozzle was used to form a 60 mm wide layer, the relative height of the layers varies from 20 to 10 mm to ensure the same thickness, considering the deformation of the lower layers. The mixture was manually inserted into the print head through a special opening. For green strength tests, samples with an area of 120×120×80 mm were printed, for strength and buildability tests, square-shaped samples with external dimensions of 220×220 mm, up to 200 mm high. Laboratory conditions at the time of printing were RH 20–30 %, and temperature 18–20 °C.

For green strength tests, the specimens were moulded after manufacturing into 150×150 mm moulds with a height of 100 mm, without a bottom base. When the moulds were filled, they were lifted immediately – the mass settled slightly and samples about 75–85 mm high were obtained for green strength tests, which were tested after a specific time – 0, 30, 60, or 120 min. The specimens were formed into 70×70×280 mm prism shapes for mechanical strength tests, with three specimens for each test direction. Three plates measuring 350×350×50 mm were formed for thermal conductivity tests.

After preparation, the samples were stored under the laboratory conditions described above. The printed samples are not covered at all, therefore, the moulded samples were demoulded after 48 h and left to cure under laboratory conditions.

2.3. Physical and Mechanical Testing

Samples for mechanical strength tests were cut from the above-mentioned printed samples, for compressive strength tests they were 70–90 mm long, 50–70 mm wide, and 50–60 mm high. To ensure a flat compressive plane, the samples were levelled with gypsum mortar before the tests. Samples 220 mm long, 70 mm wide, and 70 mm high for flexural strength were cut. At least 3 specimens were cut for each test direction. Both compressive and flexural strength were determined parallel and perpendicular to printing and moulding direction. Flexural strength was tested on moulded prisms and compressive strength on the halves of the fractured prisms using a metal plate with a defined area to limit the loading area accurately. The maximum load at the point of collapse was determined. The tests were performed with a universal testing machine *Zwick Z100*, with a load application rate of 0.5–1 mm/min.

Thermal conductivity was measured using the *LaserComp FOX600* heat flow meter according to the standard LVS EN 12667 guidelines, the test settings were – 0 °C upper plate and 20 °C lower plate. Density of both the fresh mixture as well as the material itself was determined.

Green strength was tested on both moulded and printed specimens at four different times after fabrication – 0, 30, 60, and 120 min. Sample dimensions were measured before the test. At the specified time, the specimen was placed in the compression machine mentioned above, and compressive force was applied over its entire area at a speed of 1 mm/min until the specimen was deformed to 10 % height, and a force-deformation diagram was recorded. The deformation at which the first visually observable cracks appeared was determined.

2.4. Life Cycle Assessment

The life cycle assessment (LCA) was performed following ISO 14040/44. It was done using the software *SimaPro 8*, *Ecoinvent* database was used for most of the processes. GWP100a impact assessment method was used, focusing on the global warming potential (GWP) measured in kg of CO_2 equivalents (CO_2 eq.).

2.4.1. Definition of Goal and Scope

This study aims to use LCA to determine the GHG emissions or storage potential of a 3D printed hempcrete multilayer wall element. Hempcrete is a material that has a low environmental impact, but 3D printing requires different compositions with a higher amount of binder, so a calculation must be made to find out how 3D printing affects it. Hempcrete wall elements will be compared with traditional construction wall elements from other studies with similar U-values.

To define the functional unit results from section 3.1. is used here. The thermal conductivity of moulded samples was 0.133±0.005 W/(m·K), indicating that the material is unable to provide adequate thermal resistance at average wall thickness. To solve this, hempcrete with a density of 660 kg/m^3 should be printed as an outer wall shell (similar to Contour Crafting) and the middle filled with lower density thermal insulation hempcrete (density 220 kg/m^3, λ 0.062 W/(m·K), composition – hemp:lime ratio 1:0.75 by mass, data and recipe from previous study [19]).

Two different functional units are adopted, both per m^2 of a wall, but with different U-values. Wall A with a U-value of 0.180 W/(m^2·K), which ensures normal operating conditions in a cold climate, such as in Latvia, Wall B with a U-value of 0.105 W/(m^2·K), which would be used in the construction of nearly Zero-energy buildings. The outer shell of both walls is adopted as two layers of 60 mm of high-density 3D printable hempcrete, the inner thermal insulation layer is 280 mm for Wall A and 520 mm for Wall B, as shown in Fig. 1 and Table 2. As in previous studies, the load-bearing structure in this model consists of a wooden frame consisting of two 150×50 mm wooden studs per meter and steel fittings.

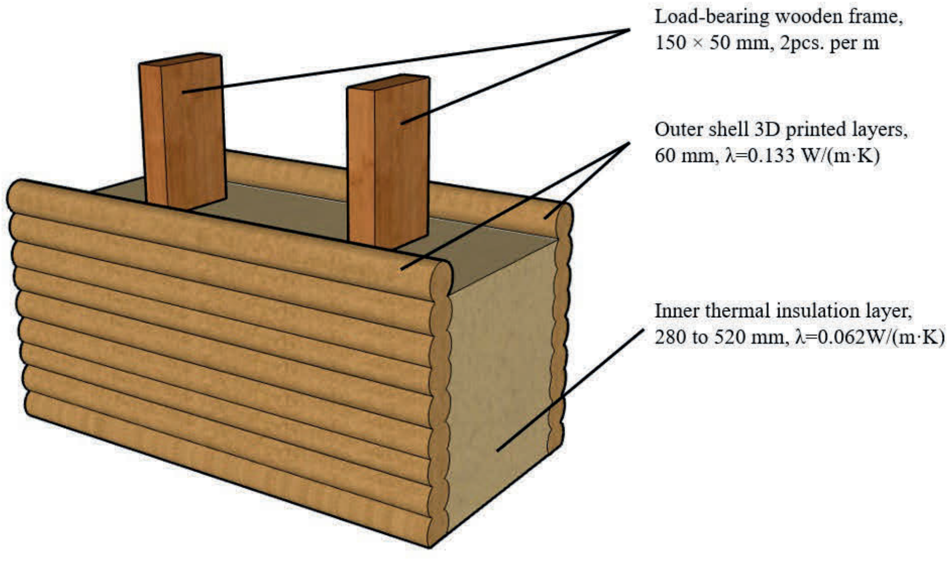

Fig. 1. Schematic 3D printed hempcrete wall fragment.

Impact for 1 m^2 of the wall with the defined U-value is calculated using 'cradle-to-gate' system boundaries. For comparison with the traditionally used materials, previous studies have been used, where walls with brick blocks and polystyrene layer [20], aerated concrete and insulated reinforced concrete [13], various insulated masonry block constructions [21] have been used.

2.4.2. Inventory Analysis

Ecoinvent database was used for most of the processes, additional processes and calculation method is described in a previously published work of the authors, where both the cultivation and processing of hemp and the production of hempcrete are described [19]. In regard to this study, the material composition was taken as described in section 2.1. Complete carbonation of the lime binder was calculated – 594 g of CO_2 per kg of $Ca(OH)_2$. CO_2 sequestration of hemp stalks is taken as 1.84 kg CO_2 per 1 kg of stalks. Additional energy for the production with the 3D printer was assumed to be the same as for mixing, but it accounted only for the outer layer, as the inner low-density thermal insulation hempcrete layer is too dry for printing and needs to be filled and tamped as traditional hempcrete.

3. RESULTS AND DISCUSSION

3.1. Testing of Physical and Mechanical Properties

Mechanical testing results are shown in Fig. 2. Looking at the results of the compressive strength test, it can be seen that the printed samples show a 23 % to 32 % lower strength in both directions than the cast ones. To explain this, an essential aspect of the sample preparation difference must be taken into account – the printed samples were cut from larger samples, similar to what is done with 3D printed samples of concrete [22]. However, during sawing, it was observed that the outer layer of the specimen formed a firm crust, but the inner part was much looser, with an incompletely set binder. The final product of hardening can explain this – $CaCO_3$, which is formed by carbonation of the sample, capturing CO_2 from the air, thus, it takes place slowly, starting from the outer layers. Thus, the 3D printed samples showed lower strength because the three edges were sawn and could not reach the same strength as the casted samples.

Flexural strength of 3D printed samples is two to three times lower, which is likely also due to the sample preparation, as the two edges of each sample were sawn. There is a bigger difference here than in the case of compressive strength because it is the outer layers that provide most of the flexural strength. To avoid the effect of sawing samples in future studies, they will be printed in special moulds to ensure the required geometry of the samples without sawing.

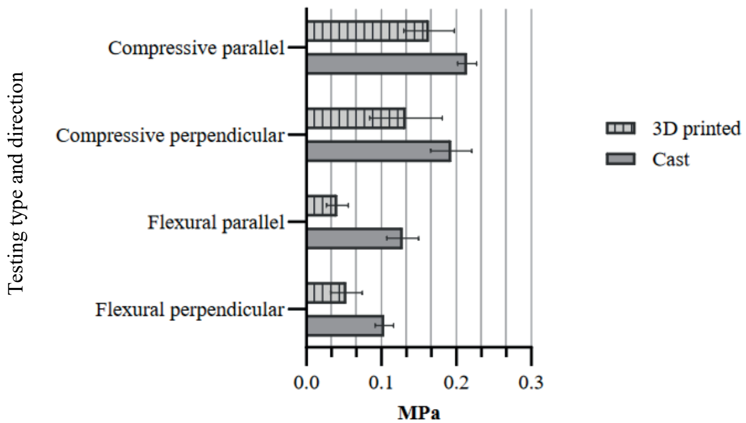

Fig. 2. Compressive and flexural strength for cast and 3D printed samples in both directions.

Fresh mixture density was 1230±10 kg/m^3, and the density of both printed and cast samples was 660±20 kg/m^3, thus no different material compaction was formed during the printing process and, therefore, it can be concluded that the printing process did not affect density. The achieved compressive strength parallel of 0.164 is sufficient to use the material as a self-bearing envelope material, as this limit is set at 0.15 MPa for hempcrete by the French hemp building rules [23]. The thermal conductivity of moulded samples was 0.133±0.005 W/(m·K).

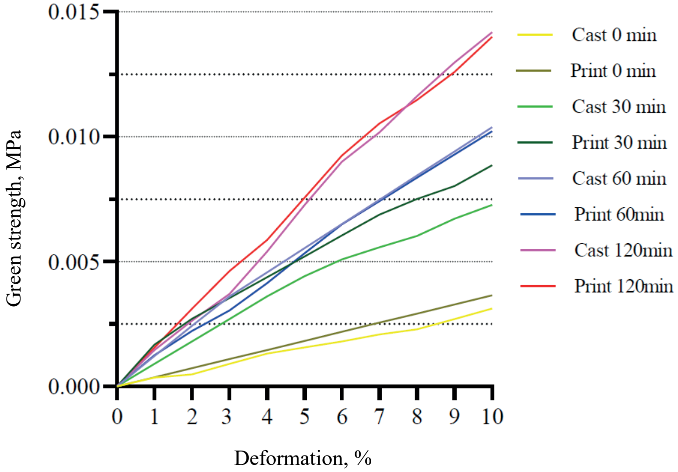

Fig. 3. Green strength of hempcrete cast and 3D printed samples at different times since manufacture.

The results of the green strength test are shown in Fig. 3. It can be seen that the green strength of the cast and printed samples is very similar, at 60 and 120 min hardening, does not differ by more than 5 %. This indicates that hempcrete printing does not significantly alter its fresh properties, and its various mixtures can be tested without printing. During the green strength tests, it could be observed that when the 30, 60, and 120 min samples deformed, the first visually observable cracks appeared at 3–4 % relative deformations, 0 min samples did not crack at all.

The results of the green strength tests are also confirmed by the buildability tests – when printing a 10-layer-high sample with a constant layer thickness of 20 mm – the sample collapses at the last layers because the previous layers are not under them, as the sample had settled by about 10 %. Buildability tests show that samples with 15 layers, variable layer height, and a total height of 200 mm can be printed without sample collapse (Fig. 4(a)), further layers could be built up after 30 min in layers of 200 mm total height, according to green strength tests. Without this interruption, the printing of higher layers results in a collapse (Fig. 4(b)).

3.2. Life Cycle Impact Assessment and Interpretation

Looking at the CO_2 emissions of such walls from a manufacturing point of view (Table 2), using LCA and previously developed and published methods [19], it can be determined that 1 m^2 of Wall A with a U-value of 0.180 W/(m^2·K) can capture 1.21 kg of CO_2 eq. making it carbon neutral. Wall B, with a U-value of 0.105 W/(m^2·K), can capture 16.7 kg of CO_2 eq. making it carbon negative. This is possible because the hemp has taken up CO_2 during its growth, and the lime binder used has carbonated during the hardening process and sequestered part of the CO_2 released during its production.

Looking at Fig. 5, a more detailed distribution of GWP between the different components of 3D printed hempcrete for both wall types is visible. Wall A sequesters less CO_2 than Wall B due to the thinner thermal insulating hempcrete layer, as hemp shives for the inner part absorbs most of the CO_2 of the hempcrete of –55.9 kg of CO_2 eq.

(a) (b)

Fig. 4. Successful buildability test of a 15-layer sample with a height of 200 mm (a), collapse when printing higher layers without interruption (b).

The printed layer together (lime+hemp+electricity) for both wall types produces 13.61 kg of CO_2 eq. regardless of the overall wall thickness because the thickness of the printed layer does not change. Most of the 120 mm thick layer emissions are caused by the lime binder of 23.7 kg of CO_2 eq. Lime binder for the inner part causes only 39 % of the emissions of the outer layer for Wall A and 73 % for Wall B. This shows that when applying 3D printing technology, it is worth increasing the wall thickness and providing a higher U-value, as both energy efficiency will improve and the carbon footprint will decrease.

Looking at the distribution of emissions by group, it can be concluded that most of the emissions are caused by the binder, the other emissions are only 18.7 % of the emissions for Wall A and 20.8 % of the emissions for Wall B. This observation is similar to previous studies on traditionally cast hempcrete, where the binder also accounted for most of the GWP impact [19].

Comparing Wall A to traditionally used building materials per 1 m^2 of a wall at similar U-values, it can be seen that hempcrete outperforms these materials (Table 3). Uninsulated autoclaved aerated concrete blocks emit 82.8 kg of CO_2 eq., while insulated reinforced sandwich structures emit 95.5 kg of CO_2 eq. [13]. Similarly, high values of 107.88 kg of CO_2 eq. are obtained in a study comparing several hempcrete construction types and a traditionally built wall of a 300 mm brick block and a 120 mm polystyrene insulation layer [20].

TABLE 2. LCA RESULTS OF 1 M^2 OF PRINTED HEMPCRETE WALLS

Wall type	**U-value,** W / (m^2·K)	**Total thickness,** mm	**Outer layer thickness,** mm	**Inner layer thickness,** mm	**GWP per m^2,** kg of CO_2 eq.
Wall A	0.180	400	120	280	–1.21
Wall B	0.105	640	120	520	–16.7

Using hemp blocks, a wall with the same thermal transmittance produces 44 kg of CO_2 eq., which is explained in the study by the high negative impact of the used binder – hydraulic lime [19]. Other types of walls that use hempcrete with a traditional formwork technology and hemp shives as a filler show a GWP of –30.91 to 15.22 kg of CO_2 eq. per m^2 of wall. In a study by Di Capua *et al.* [19] a hempcrete wall with a similar U-value produced 15.22 kg of CO_2 eq., but this study did not consider lime carbonation; if it were considered, then this wall would also be CO_2 negative.

Wall B similarly outperforms walls made of insulated lightweight concrete, hollow ceramic, and aerated concrete blocks with a U-value of 0.105 W/(m^2·K) (Table 3). These walls are 514 to 614 mm thick and emit 83.41 to 146.71 kg of CO_2 eq. [21]. The comparison shows that the results obtained in this study align with other studies on the GWP of hempcrete materials and that such bio-based self-bearing envelope and thermal insulation building materials have significantly lower CO_2 emissions than traditionally used wall materials.

It must be noted that such hempcrete as the inner low-density thermal insulation hempcrete is not usually used in traditional hemp construction as it has too low a strength and cannot be used without an enclosing shell structure. Thus, 3D printing makes it possible to make greater use of hempcrete material, reducing its density and the amount of binder consumed.

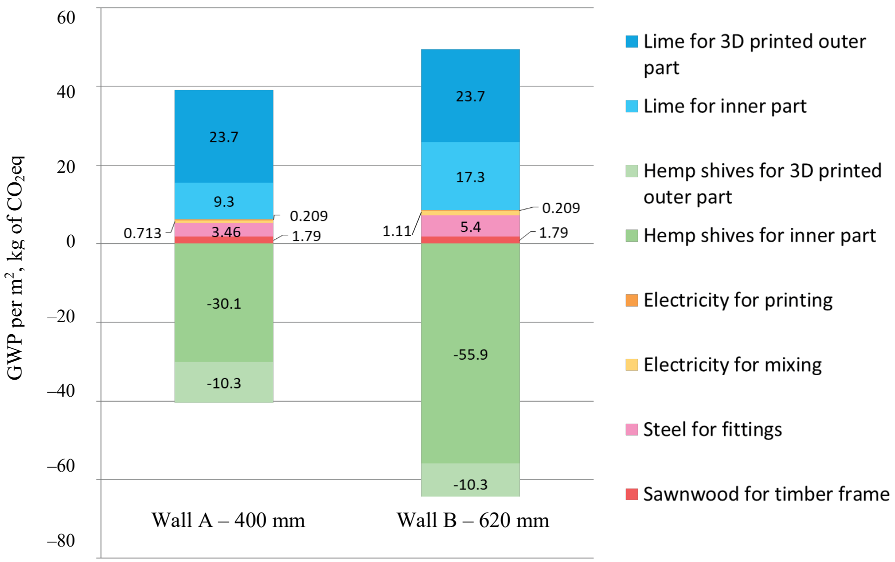

Fig. 5. Distribution of GWP between the different components of 3D printed hempcrete walls.

TABLE 3. GWP OF ALTERNATIVE WALLS WITH SIMILAR U-VALUE

Wall type	**U-value,** W/(m^2·K)	**Total thickness,** mm	**GWP per m^2,** kg of CO_2 eq.	**Source**
Wall A	**0.180**	**400**	**–1.21**	**This study**
Uninsulated autoclaved aerated concrete blocks	0.170	500	82.80	[13]
High Performance Foam Concrete	0.180	600	91.50	[13]
Reinforced concrete + stone wall	0.180	320	95.50	[13]
Brick block + polystyrene insulation	0.200	420	107.88	[19]
Hempcrete wall	0.200	300	15.22	[19]
Hemp Block wall	0.200	300	44.00	[19]
Traditional hempcrete wall	0.190	300	–36.08	[24]
Magnesium oxychloride cement + hemp	0.180	344	–12.68	[19]
Formulated hydrated lime + hemp	0.180	453	–30.91	[19]
Wall B	**0.105**	**640**	**–16.70**	**This study**
Lightweight concrete + stone wool	0.105	564	146.71	[21]
Lightweight concrete + EPS	0.105	514	111.06	[21]
Hollow ceramic blocks + stone wool	0.105	604	117.96	[21]
Hollow ceramic blocks + EPS	0.105	542	101.50	[21]
Aerated concrete blocks + stone wool	0.105	614	100.91	[21]
Aerated concrete blocks + EPS	0.105	554	83.41	[21]

4. CONCLUSIONS

Five main conclusions can be drawn from the results:

1. Hempcrete is 3D printable at a density of 660 kg/m^3, has sufficient buildability and strength to form an outer shell layer for self-supporting walls, the inner layer of which can be filled with less dense hempcrete with a density of 220 kg/m^3, providing adequate thermal resistance at an overall wall thickness of 400–640 mm;
2. Such walls have a significantly lower environmental impact as they can store from 1.21 to 16.7 kg of CO_2 eq. per m^2, in contrast to the walls of traditionally used materials, which emit up to 147 kg of CO_2 eq. per m^2;
3. The fresh binder properties of the 3D printed samples are similar to the properties of the cast samples, thus facilitating their testing and preliminary development of new formulations without printing;
4. The mechanical strength properties of the 3D printed samples are lower than the properties of the cast samples, by 31 % in compressive and 67 % in flexural strength due to outer carbonation layer and specimen preparation using sawing. To overcome this problem in the future studies, samples will be printed in special moulds;
5. At 660 kg/m^3 density, hempcrete can be printed in at least 15 layers with a total height of 200 mm, further layers can be built up after 30 min. This speed is sufficient for printing walls and elements for real construction needs.

The use of hempcrete material in combination with 3D printing opens up a wider range of uses for this material and the possibility of eliminating the negative impact of the construction industry on the environment. This study did not consider the optimization of printable forms to reduce material consumption, which would have an additional positive effect compared to traditionally used building materials but will be tested in future studies.

Future research will focus on the possibility of adding dry hemp shives to the print head, where they would be mixed with a binder that has already been mixed and fed to the print head with a pump. This would facilitate the mixing process and possibly improve buildability, as the dry shives would absorb the technologically necessary water soon after printing, allowing the successive layers to be printed faster.

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