SBE16 HAMBURG

STRATEGIES
STAKEHOLDERS
SUCCESS FACTORS

ZEBAU

Conference Proceedings

Sustainable Built Environment Conference 2016 in Hamburg

Strategies, Stakeholders, Success factors

7th - 11th March 2016

Karlsruhe Institute of Technology

HOCHSCHULE FÜR ANGEWANDTE WISSENSCHAFTEN MÜNCHEN

HCU HafenCity Universität Hamburg

www.kit.eu

Program Overview

	Monday 7.3.2016	Tuesday 8.3.2016	Wednesday 9.3.2016	Thursday 10.3.2016	Friday 11.3.2016
8.00-9.00 a.m.		Registration	Registration	Registration	
9.00-10.30 a.m.		Opening Keynotes	Scientific sessions / Housing Industry Day	Scientific sessions / Day of Architecture, Planning & Engineering	PhD Session / Excursions
10.30-11.00 a.m.		Coffee	Coffee	Coffee	Excursions
11.00 a.m.-12.30 p.m.		Scientific sessions / Day of Municipalities	Keynote Session UN Climate Change Conference	Scientific sessions / Day of Architecture, Planning & Engineering	PhD Session / Excursions
12.30-2.00 p.m.		Lunch	Lunch	Final Session / Lunch	
2.00-3.30 p.m.	Excursions / Pre-Registration	Scientific and special sessions / Day of Municipalities	Scientific and special sessions / Housing Industry Day	Final Session / Excursions / Day of Architecture, Planning & Engineering	PhD Session
3.30-4.00 p.m.	Excursions / Pre-Registration	Coffee	Coffee	Excursions / Coffee	
4.00-5.30 p.m.	Excursions / Pre-Registration	Scientific and special sessions / Day of Municipalities	Scientific and special sessions / Housing Industry Day	Excursions / Day of Architecture, Planning & Engineering	
5.30-7.00 p.m.	Warm-up and exhibition opening	Welcome and Networking-Reception for all participants (Handelskammer)	Get Together and Award Ceremony (Holcim Study Award)		

Scientific Session

Session in German language

PhD Session

SBE16 Hamburg

International Conference on Sustainable Built Environment Strategies – Stakeholders – Success factors

7th - 11th March 2016

Conference Proceedings

Organised by

ZEBAU

Karlsruhe Institute of Technology

Hochschule für angewandte Wissenschaften München

HCU HafenCity Universität Hamburg

Imprint

Conference organisers

ZEBAU – Centre for Energy, Construction, Architecture and the Environment GmbH

www.zebau.de

In cooperation with

Supported by

Edited by: ZEBAU – Centre for Energy, Construction, Architecture and the Environment GmbH, Große Elbstraße 146, 22767 Hamburg, Germany

This book was prepared from the input files supplied by the authors.

2016

Printed on 100% recycled paper.
Druckerei in St. Pauli, Große Freiheit 70, 22767 Hamburg, Germany

ISBN 978-3-00-052213-0
DOI: 10.5445/IR/1000051699

Hempcrete from cradle to grave: the role of carbonatation in the material sustainability

Alessandro Arrigoni
Eng.
Politecnico di Milano
Italy
alessandro.arri-
goni@polimi.it

Co-Author without Photo: Dr. Renato Pelosato, Politecnico di Milano, Italy, renato.pelosato@polimi.it; Prof. Giovanni Dotelli, Politenico di Milano, Italy, giovanni.dotelli@polimi.it

Summary

The goal of reducing buildings impact to the environment is achieved by minimizing the energy consumption and through the employment of sustainable materials. However, the sustainability of building materials is assessed too many times considering a single phase of the material lifecycle (e.g. the use phase for good insulating materials). Even “LCA” studies focus sometimes on a single stage of the lifecycle, but this approach is particularly wrong for materials that improve or reduce their environmental performance during the operational phase or at the end of the building’s life. This is the case for materials containing lime, whose strength and sustainability increase theoretically along with the carbonatation process. An innovative building material containing lime is the hempcrete brick: a non-structural composite material obtained from a mixture of hemp shives (woody core of the hemp stalk) and a lime based binder; this material shows good thermal performances (λ: 0.07 W/m·K) and moisture buffering capacity. LCA studies about hempcrete materials either leave out the carbonatation process from the assessment or assume that lime is fully re-carbonated in the use phase of the building. The goal of our study is to assess the real rate of carbonatation of hempcrete bricks in order to include the results in a thorough LCA study and to understand the weight this process can have in the overall sustainability of the material. The carbonatation rate has been evaluated on bricks produced by the Italian company Equilibrium Srl. The degree of carbonatation is evaluated through X-ray diffraction on samples extracted at regular intervals from the brick production up to 5 months. Carbonatation depth profiles are obtained too. Results show the importance of evaluating the behavior of a material in all the phases of the lifecycle and could be used for future LCA studies on hempcrete materials exposed to similar conditions.

Keywords: hempcrete, LCA, carbonatation, carbon footprint, building materials

1. Introduction

As recently reported [1, 2], the building sector accounts for about 32% of global energy use and for about 19% of energy-related greenhouse gas emissions. Therefore, in the field there is a consensus towards the reduction of non-renewable energy sources exploitation and mitigation of GHG emissions, which is promoting the search for alternative and less impacting materials to replace conventional ones [3]. Natural materials are one of these options, as they would allow the reduction of non-renewable resource depletion and of environmental impacts related to fossil fuel consumption. To this purpose, hemp is an industrial crop that suits perfectly the building sector requirements [4]; indeed, it is a natural product already used as construction material [5].

Hemp stem consists of a woody core surrounded by an outer skin containing long and strong fibres, and two main products can be obtained by its processing: hemp hurds (or shives) and hemp fibres. Hemp fibres are the most valuable part of the plant, and in the building industry they are usually used as insulation products, although Fibre Reinforced Concrete (FRC), a composite concrete material consisting of a hydraulic cement matrix reinforced with discontinuous discrete fibres dates back to 1960s [6]. However, the use of hemp fibre and shiv in concrete and cement mortars is being seriously considered by many authors [7-9].

On the contrary, hemp lime-based products have been extensively used as construction materials. Indeed, hemp lime composites started being used in France throughout the 1990s and now there are many examples of hemp lime constructions spreading around in other countries [10]. Hemp lime composite, often referred to as hemp concrete or simply hempcrete, is a building material formed from the mixture of hemp hurds as aggregate and lime based binders, which finds application for insulating walls or insulation layers for floors and roofs and, combined with a load bearing structure, for perimetral masonry.

In the recent literature, various mechanical properties have been tested on lab scale specimens: compressive strength, flexural strength, and flexural toughness among others. Clearly, mechanical properties strongly depend on the binder used and on the addition of fillers and aggregates. A summary of the mechanical properties of the hemp fibre/hurds lime/cement composites can be found in a recent review [4]. Recently, there has been also un upsurge of interest in thermal [11] and hygrothermal properties of hemp-lime concretes and buildings [12-16].

Few studies on sustainability of hemp-based building materials have appeared in the recent literature up to now [10, 17-19], and those considering specifically hemp lime products account for the CO_2 sequestered during lifetime as the maximum possible value, i.e. supposing full carbonatation of the lime binder. However, a recent study has highlighted that in hemp-based mortars with aerial and natural hydraulic lime mixes hardening is delayed because of an insufficient amount of water available to the matrix of the mixes from the start [20].

The aim of the study is to assess the environmental impacts of hempcrete bricks produced by the Italian company Equilibrium (www.equilibrium-bioedilizia.it) located in the province of Bergamo, and to understand the role that carbonatation could play in their LCA analysis.

2. Materials

The hempcrete bricks considered in the study are composed of dolomitic lime and hemp shives, with a ratio by mass binder to hemp of 1.3.

Hempcrete bricks can be used without the support of other materials: combined with a load bearing structure (pillars or frame), they can be used as a perimetral masonry. The dimensions of the bricks here considered are 50 cm x 40 cm (faces exposed) x 25 cm (thickness).

The bricks have very good insulation properties with a thermal conductivity of 0.07 W/m·K. Moreover, the bricks are resistant to fire, to frost, to insects and to rodents. They are reusable or recyclable at the end of the building life. Finally, hempcrete bricks have good acoustic and psychrometric properties.

3. Methodology

3.1 LCA

The LCA presented in this paper follows the methodology defined by international and European norms: ISO 14040, ISO 14044 and EN 15804. For the LCA anlysis' implementation the software SimaPro 8.0.5 was used.

3.1.1 Functional unit

The functional unit considered in this study is the square meter of non-load bearing wall made of hempcrete bricks. The overall heat transfer coefficient of the wall (U-value) is 0.27 $W/m^2 \cdot K$, equal to the limit imposed by the Italian law (D.M. 11 Marzo 2008 [24]) for retrofitted buildings in the area of Milan (Climatic zone E). The thickness of the wall is 0.25 m and both faces of the wall are supposed to be in contact with air.

3.1.2 Data quality and system boundaries

Primary data are used for the production phases inside the factory ("from gate to gate") and secondary data for the production of the materials used in the mixture of the brick. The impacts related to lime production are extrapolated from the Ecoinvent database. The environmental impacts related to the production processes of hemp hurds are taken from a previous LCA study on hemp cultivation [18]. The producing company supplied all the data related to transport and packaging processes.

The LCA considers the impacts related to the production phase of the wall and its use phase. The impacts related to the transport of the bricks on the building site and the erection of the wall are not considered. Even though the bricks can be reused as they are after the building demolition, the end of life of the bulding is difficult to forecast and therefore it was not considered.

3.1.3 Impact indicators

Three midpoint indicators are considered in the study: 1) CML-IA Baseline (7 impact categories); 2) Cumulative Energy Demand (CED, in MJ); 3) Greenhouse Gas Protocol (GGP, in kg CO_2-eq).

3.2 Carbonatation

The carbonatation of the hempcerte brick vs time was investigated via semi-quantitative X-Ray Powder Diffraction (XRPD) analysis. The phase composition of samples extracted at regular time intervals was studied, starting from the brick production up to 5 months (30, 75, 110 and 150 days). Carbonatation was investigated also as a function of the brick depth: at each time, 5 portions of brick were extracted at different depths (0-2, 2-4, 4-6, 6-8 and 8-10 cm), crushed and sieved to separate the binder fraction from the hemp. Figure 1 shows the brick used for the analysis and the hole left in the brick after the coring of the sample.

The XRD pattern of each fraction was recorded with a Bruker D8 Advance Diffractometer using graphite monochromated Cu $K\alpha$ radiation. The measurement interval was 10-50 ° 2θ, with measurement steps of 0.02 °2θ and a measurement time of 1 s/step. The peaks used for the semi-quantitative analysis were the *(001)* peak of $Ca(OH)_2$ at 2θ = 18.048, the *(001)* peak of $Mg(OH)_2$ at 2θ = 18.587, the *(104)* peak of $CaCO_3$ at 2θ = 29.406 and the *(200)* peak of MgO at 2θ = 42.917. These peaks were also recorded with a measurement time of 4 s/step to increase the counting statistics. The integrated intensities of the reported peaks were evaluated via peak profile fitting of the experimental data, performed with the software Topas+ 2.1 (Bruker AXS®) using a Pseudo-Voigt profile function. The obtained integrated intensities were used for the semi-quantitative analysis of phases using the the generalized Reference Intensity Ratios (RIR) method. Provided that all the phases are taken into account, the intensity of the peaks can be related to the amount of each phase in the mixture through the generalized RIR equation [25]:

$$\chi_\alpha = \frac{I_{i\alpha}}{RIR_\alpha I_{i\alpha}^{rel}} \left(\frac{1}{\sum_{k=1}^{n(phases)} \frac{I_{i,k}}{RIR_k I_{i,k}^{rel}}} \right) \tag{1}$$

where χ_α is the weight fraction of the phase α, $I_{i\alpha}$ is the integrated intensity of the i^{th} peak of the phase α, $RIR\alpha$ is the Reference intensity Ratio of the phase α respect to corundum (literature values were adopted) and $I_{i\alpha}^{rel}$ is the relative intensity of the i^{th} peak respect to the most intense peak of the same phase α.

The results of the semi-quantitative analysis of each portion was then used to evaluate the amount of calcium hydroxide and calcium carbonate at each depth in the brick and finally in all the brick body.

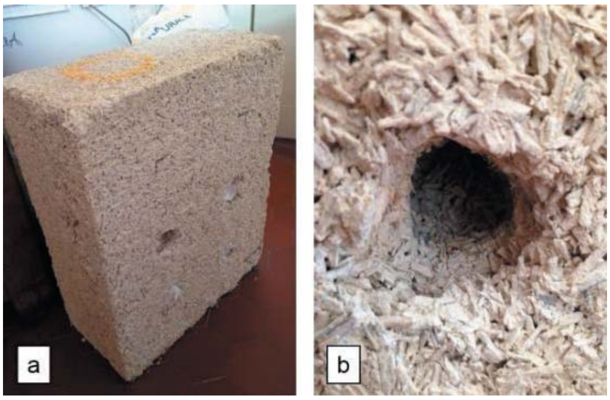

Figure 1: (a) Hemp brick sample, (b) hole left in the brick after sample coring

3. Results

3.1 LCA “from cradle to gate”

3.1.1 Hempcrete bricks production

The hempcrete bricks considered in the study are produced by the Italian company Equilibrium (www.equilibrium-bioedilizia.it), located in the province of Bergamo. Hemp is cultivated in the province of Turin by the company Assocanapa and the quarry of the dolomite is situated 320 km away from the bricks’ production site, in the province of Cuneo. Once arrived to the production site, the components of the mixtures are blended in a mixer with water. After the mixing process, the hempcrete mixture is pressed and the resulting bricks are arranged on shelves to cure and give them enough strength to be transported to the construction site and installed. Before the transportation, the bricks are wrapped in a thin film of polyethylene.

3.1.2 Greenhouse Gas Protocol

Figure 2 shows the results of the production of a square meter of hempcrete wall in terms of greenhouse gases. The method used is the Greenhouse Gas Protocol, developed by the World Resources Institute. The results show that the amount of greenhouse gas emissions in terms of kg of carbon dioxide equivalents due to the production phase are lower than the amount of carbon dioxide absorbed by the hemp during its growth through the photosynthesis process (CO_2 uptake). About 83% of the fossil CO_2 emissions are related to the lime production and in particular to the calcination process occurring in kilns at very high temperatures. The contributions of CO_2 emissions from biogenic source and the ones due to land transformation are negligible, as we can see in Figure 2.

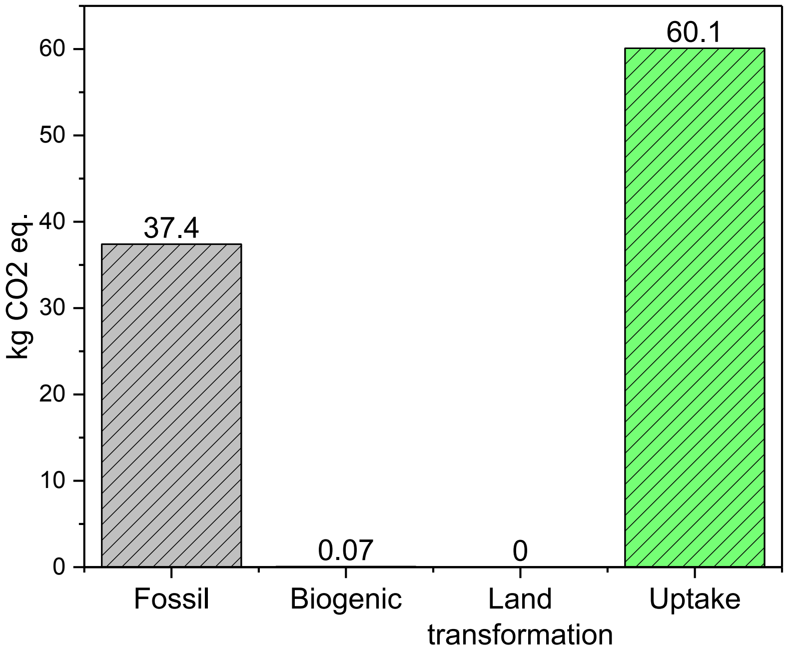

Figure 2: Greenhouse Gas Procol results (FU: 1 m^2 wall)

3.1.3 CML-baseline results

Table 1 shows the CML-IA baseline indicator results for the seven environmental impact categories required by the UNI 15804 to assess the sustainability of building products. As for the greenhouse gases' emissions, main contributions for all the impact categories except abiotic depletion derive from lime production processes. Depletion of abiotic resources is mainly due to the consumption of lead in the production process of fertilizers and to the consumption of uranium, used to produce part of the electricity consumed in Italy.

Table 1: CML-baseline indicator results

Impact Category	Unit	Hempcrete wall [1 m^2]
Abiotic depletion	kg Sb eq	2.24E-07
Abiotic depletion (fossil fuels)	MJ	304
Global Warming Potential (GWP100a)	kg CO_2 eq	37.4
Ozone Layer Depletion (ODP)	kg CFC-11 eq	3.35E-06
Photochemical oxidation	kg C_2H_4 eq	6.80E-03
Acidification	kg SO_2 eq	6.23E-02
Eutrophication	kg PO_4--- eq	3.80E-03

3.1.4 Cumulative Energy Demand

Figure 3 shows the results for the Cumulative Energy Demand method. The very high value of the energy from biomass is due to the significant presence of hemp in the product. It is important to underline that the binder-hemp ratio in the brick is in mass. Since hemp hurds' density is lower than lime's density, the volume occupied by the hemp in the brick is much higher than the one occupied by the binder. The contributions of the energy from nuclear and other renewable sources (wind, water and sun) derive from the consumption of electric energy in the brick manufacture and, therefore, from the Italian electricity generation mix.

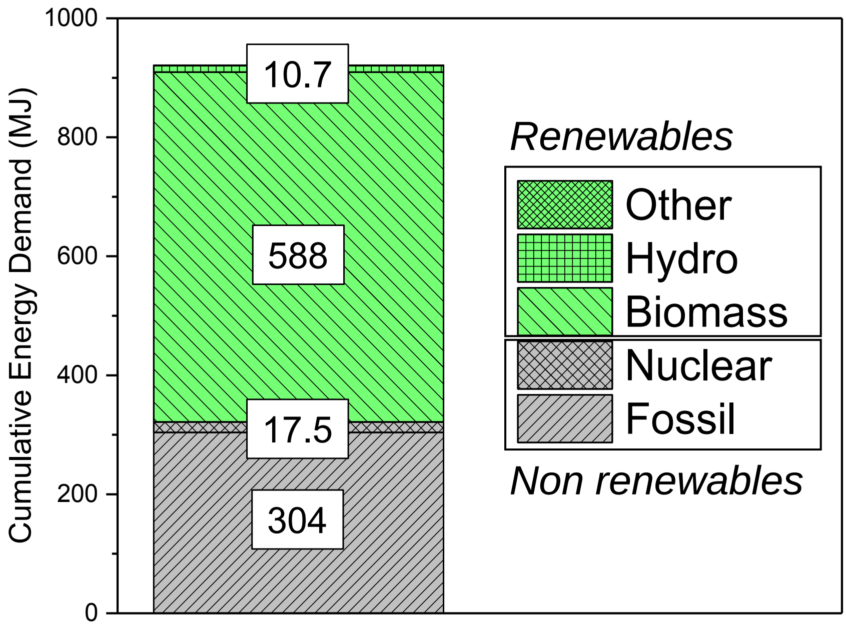

Figure 3: CED results

3.2 Carbonatation results

In each sample, the identified phases in the binder fraction are $Ca(OH)_2$, $CaCO_3$, MgO and $Mg(OH)_2$. The amount of each phase was quantified in the 5 fractions extracted at increasing depth (0-2, 2-4, 4-6, 6-8 and 8-10 cm) at each time interval (30, 75, 110 and 150 days). At each time, the amount of $Ca(OH)_2$ and $CaCO_3$ were considered to assess the extent of carbonatation in the hempcrete bricks.

Figure 4 reports the XRPD patterns of the binder at different depths after 75 days of ageing. Only the peaks of $Ca(OH)_2$ and $CaCO_3$ are indicated for sake of simplicity.As expected, the amount of $Ca(OH)_2$ increases moving from the surface layer to the inner layers at any aging time; after 30 days for example, $Ca(OH)_2$ is 47% at 0-2 cm depth and 62% at 8-10cm depth. $CaCO_3$ show an opposite trend (15% is found in the surface layer, and drops down to about 6% in the inner layer, at 30 days). Similar trends are found at any ageing time.

Figure 5 reports the amounts of $Ca(OH)_2$ and $CaCO_3$ in the brick as a function of ageing time. Analysing the carbonatation respect to age of samples, a significant transformation of $Ca(OH)_2$ into $CaCO_3$ is revealed in the outermost layer (from 47% $Ca(OH)_2$ and 15% $CaCO_3$ at 30 days to 14% $Ca(OH)_2$ and 38% $CaCO_3$ at 150 days). A similar behavior is observed in the 2-4 cm and 4-6 cm layers, but in a much lesser extent. In the innermost layers, instead the composition remains nearly unchanged up to the investigated ageing time. Therefore, in a 150 days timeframe, carbonatation appears to be significant only in the external part of the brick.

By integrating the results of each layer on the whole brick volume, the ratio of carbonatation with respect to the maximum possible carbonatation can be calculated; in this respect, Pretot et al. assumed that during the brick lifetime (a conventional period of 100 years is assumed [19]) a complete transformation of $Ca(OH)_2$ to $CaCO_3$ can be achieved. In a functional unit of 1 m^2 of wall with bricks of 25cm thickness with two sides exposed to air, the expected carbonation after 150 days is about 9% (i.e. 9% of $Ca(OH)_2$ has reacted with CO_2 to yield $CaCO_3$). Quantitatively, this means about 1.7 kg CO_2 adsorbed per m^2 of wall.

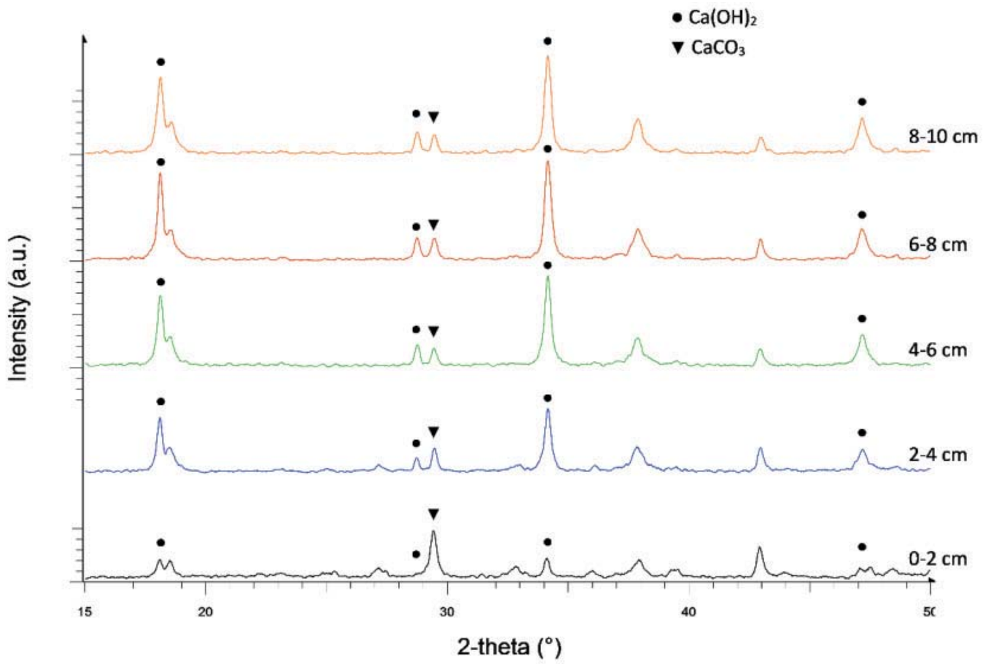

Figure 4: XRPD patterns of the binder at different depths after 75 days

Figure 5 shows the amount of $Ca(OH)_2$ and $Ca(CO)_3$ vs time. The points at day 0 represent the amount of the two chemical compounds before the process of blending (i.e. in the dolomitic lime). When water is added to the mixture, additional $Ca(OH)_2$ is formed from the chemical reaction between the dolomite and water. From the figure it is clear how the $Ca(OH)_2$ amount decreases with time, while $CaCO_3$ increases

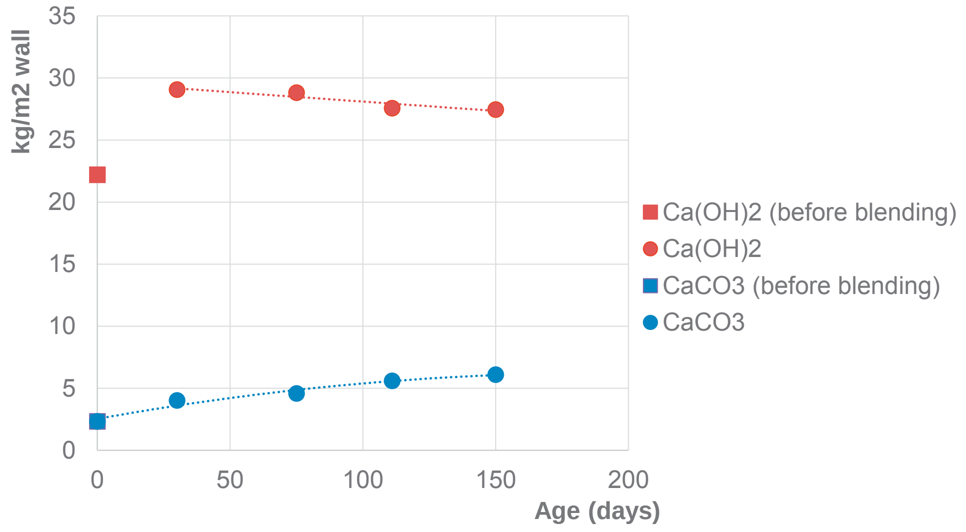

Figure 5: carbonatation m^2 wall vs time

3.3 Hemp brick wall operational phase

To extend the sustainability analysis of the hemp bricks wall from a “cradle to gate” perspective to a “cradle to grave” one, the operational phase of the system must be evaluated. Hempcrete is a recently developed material and very little is known about its durability. However, due to the presence of lime in the mixture, the mechanical performances of the wall exposed to air must increase along with the carbonatation process and, therefore, with time. Moreover, the material is resistant to fire, frost, insects and rodents. For the above-mentioned reasons, we consider that the wall does not require any maintenance during its operational phase. Furthermore, considering that the bricks can be reused as they are after the demolition of the building, no negative environemental impacts are added to the ones generated during the production phase of the wall. Even though we do not consider any further environmental impact during the use phase of the wall, the carbonatation process could generate environmental benefits. Through the process of carbonatation, the wall can absorb in fact carbon dioxide from the atmosphere and stock it in the brick for the rest of its lifetime. Knowing the amount of $Ca(OH)_2$ at the time of the brick production, it is possible to estimate the total amount of CO_2 that the wall could uptake during its lifetime. Moreover, thanks to the carbonatation analysis described in the paragraph 3.2, it will be possible to draw the profile of carbonatation of the wall with time. Since the brick we considered in this study is only 150 days old, it is too premature to draw the carbonatation profile of the material. However, thanks to the analysis already performed it is possible to estimate the amount of carbon dioxide absorbed by the wall in the first months and draw the first conclusions.

In Figure 6 is represented a comparison between the emissions of fossil CO_2 equivalents in the atmosphere throughout the lifecycle of the hempcrete wall and the total amount of CO_2 that the wall has removed in its lifetime from the atmosphere thanks to the photosynthesis and the carbonatation processes. In this way, it is possible to estimate whether the wall is neutral, negative or positive in terms of contribution to global warming. Figure 6 shows that, after the production phase, no further contribution is added on the stack of the fossil CO_2 eq. emissions. On the contrary, on the stack of the CO_2 uptake, the contribution related to the carbonatation of the bricks during the use phase of the wall appears. In the stack, two different contributions are added: the amount of carbon dioxide already absorbed by the wall after 150 days and the amount of CO_2 that the brick could absorb if all the $Ca(OH)_2$ would turn into $CaCO_3$ in the wall lifetime. In the first 150 days, 1.7 kg of CO_2 are already absorbed by each squared meter of hempcrete wall. The amount of CO_2 absorbed in the first 150 days is approximately 9% of the total CO_2 that the wall could absorb.

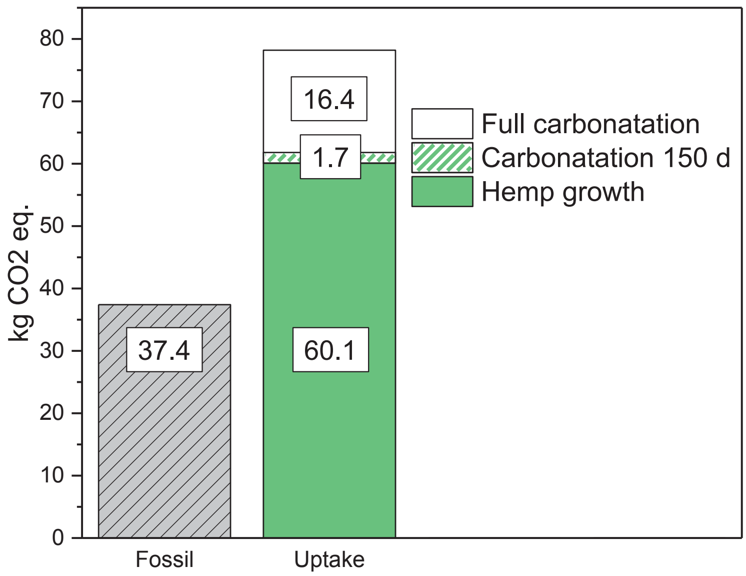

Figure 6: CO_2 fossil emissions vs uptake (FU: 1 m^2 hempcrete wall)

4. Discussion

Thanks to the X-ray diffraction analysis on hempcrete brick samples, it was possible to estimate the amount of CO_2 that a hempcrete wall in contact with air absorb in the first 5 months. After 150 days from bricks' production, the ratio in terms of greenhouse gases' emissions is 1.65 kg of CO_2 absorbed per kg of CO_2 emitted. The ratio could exceed the 2 kg CO_2 eq. absorbed/kg CO_2 eq. emitted if all the $Ca(OH)_2$ available in the brick carbonatated. Throughout its lifecycle, the hempcrete wall has a negative balance in terms of global warming potential and it is therefore acting as a carbon sink. Every m^2 of hempcrete wall can have a net positive balance that goes from 23 kg of CO_2 subtracted from the atmosphere (with no carbonatation) up to 41 kg (if the wall is fully carbonatated).

5. Conclusion

According to the results obtained some conclusions can be drawn:

- The LCA analysis of the hempcrete brick production (from cradle to gate) show that the main environmental impacts derive from the lime calcination process. The GGP results show that the amount of greenhouse gas emissions due to the production phase are lower than the amount of carbon dioxide absorbed by the hemp during its growth.
- The X-ray diffraction analysis of samples extracted from the brick at regular intervals allowed to obtain a quantitative evaluation of the carbon dioxide absorbed by the brick in the first 5 months. After 5 months 1.7 kg of CO_2 are already absorbed by each squared meter of hempcrete wall. In a functional unit of 1 m^2 of wall with bricks of 25 cm thickness with two sides exposed to air, the expected carbonation after 150 days is about 9%.
- Thanks to the results obtained with the carbonatation analysis, it was possible to extend the LCA study from a “cradle to gate” approach to a “cradle to grave” one. The LCA results indicate that throughout its lifecycle, the hempcrete wall has a net negative balance in terms of global warming potential. The wall can therefore act as a carbon sink, with a net balance that goes from 23 kg of CO_2 subtracted to the atmosphere (with no carbonation) to 41 kg if the wall is fully carbonatated.
- The carbonatation in the bricks' points distant from the surface exposed to air after 150 days seems null. Even though 150 days is a too short period to draw conclusions on the carbonatation profile of the material, the carbonation in the inner layers of the wall appears to be a very slow process. Moreover, the carbonatation process could be hampered if a plaster was used to cover the hempbrick wall.

6. References

[1] IPCC, 2014: Contribution of Working Group III to the 5th Assessment Report of the Intergovernmental Panel on Climate Change. 2014.

[2] International Energy Agency. Key world energy statistics. 2014. 2014.

[3] PACHECO-TORGAL F., "Eco-efficient construction and building materials research under the EU Framework Programme Horizon 2020", *Construction and Building Materials*, Vol. 51, 2014, pp. 151-162.

[4] INGRAO C., LO GIUDICE A., BACENETTI J., TRICASE C., DOTELLI G., FIALA M., SIRACUSA V., and MBOHWA C., "Energy and environmental assessment of industrial

hemp for building applications: A review", *Renewable and Sustainable Energy Reviews*, Vol. 51, 2015, pp. 29-42.

[5] BEVAN R., and WOOLLEY T., "Hemp lime construction – a guide to building with hemp lime composites", Bracknell, UK: IHS BRE Press; 2008.

[6] LI Z. J., WANG L. J., and WANG X. G., "Compressive and flexural properties of hemp fiber reinforced concrete", *Fibers and Polymers*, Vol. 5, No. 3, 2004, pp. 187-197.

[7] MOSTEFAI N., HAMZAOUI R., GUESSASMA S., AW A., and NOURI H., "Microstructure and mechanical performance of modified hemp fibre and shiv mortars: Discovering the optimal formulation", *Materials & Design*, Vol. 84, 2015, pp. 359-371.

[8] DIQUÉLOU Y., GOURLAY E., ARNAUD L., and KUREK B., "Impact of hemp shiv on cement setting and hardening: Influence of the extracted components from the aggregates and study of the interfaces with the inorganic matrix", *Cement and Concrete Composites*, Vol. 55, 2015, pp. 112-121.

[9] BALČIŪNAS G., PUNDIENĖ I., LEKŪNAITĖ-LUKOŠIŪNĖ L., VĖJELIS S., and KORJAKINS A., "Impact of hemp shives aggregate mineralization on physical–mechanical properties and structure of composite with cementitious binding material", *Industrial Crops and Products*, Vol. 77, 2015, pp. 724-734.

[10] IP K., and MILLER A., "Life cycle greenhouse gas emissions of hemp–lime wall constructions in the UK", *Resources, Conservation and Recycling*, Vol. 69, 2012, pp. 1-9.

[11] COLLET F., and PRETOT S., "Thermal conductivity of hemp concretes: Variation with formulation, density and water content", *Construction and Building Materials*, Vol. 65, 2014, pp. 612-619.

[12] WALKER R., and PAVIA S., "Moisture transfer and thermal properties of hemp-lime concretes", *Construction and Building Materials*, Vol. 64, 2014, pp. 270-276.

[13] STRANDBERG-DE BRUIJN P., and JOHANSSON P., "Moisture transport properties of lime-hemp concrete determined over the complete moisture range", *Biosystems Engineering*, Vol. 122, 2014, pp. 31-41.

[14] COLLET F., and PRETOT S., "Experimental highlight of hygrothermal phenomena in hemp concrete wall", *Building and Environment*, Vol. 82, 2014, pp. 459-466.

[15] BARCLAY M., HOLCROFT N., and SHEA A. D., "Methods to determine whole building hygrothermal performance of hemp-lime buildings", *Building and Environment*, Vol. 80, 2014, pp. 204-212.

[16] MAALOUF C., LE A. D. T., UMURIGIRWA S. B., LACHI M., and DOUZANE O., "Study of hygrothermal behaviour of a hemp concrete building envelope under summer conditions in France", *Energy and Buildings*, Vol. 77, 2014, pp. 48-57.

[17] BOUTIN M.-P., FLAMIN C., QUINTON S., GOSSE G., and INRA L. Etude des caractéristiques environnementales du chanvre par l'analyse de son cycle de vie. Paris: Ministere de l'Agricolture et de la Peche 2006. p. 60.

[18] ZAMPORI L., DOTELLI G., and VERNELLI V., "Life Cycle Assessment of Hemp Cultivation and Use of Hemp-Based Thermal Insulator Materials in Buildings", *Environmental Science & Technology*, 2013, pp. 130619154653008.

[19] PRETOT S., COLLET F., and GARNIER C., "Life cycle assessment of a hemp concrete wall: Impact of thickness and coating", *Building and Environment*, Vol. 72, 2014, pp.

[20] ARIZZI A., CULTRONE G., BRÜMMER M., and VILES H., "A chemical, morphological and mineralogical study on the interaction between hemp hurds and aerial and natural hydraulic lime particles: Implications for mortar manufacturing", *Construction and Building Materials*, Vol. 75, 2015, pp. 375-384.

[24] D.M. 11 March 2008, G.U No. 66, 18 March 2008 (in Italian).

[25] LIFSHIN E., "X-ray Characterization of Materials": Wiley; 2008.