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Abstract: To counter the negative environmental, particularly, greenhouse gas emission impact generated by the construction industry, many low-impact materials are being produced and researched, having neutral CO2 emissions and also low thermal conductivity in case of insulation materials. One of these materials is lime-hemp concrete, a self-bearing bio-based insulation material with low thermal conductivity and good CO2 uptake but with weak mechanical properties. In the present work, alternative magnesium binders are proposed for hemp concrete to substitute the traditionally used lime binder, comparing the environmental impact of these binders with the focus on their global warming potential (GWP). In order to make the comparison, experimental mixtures with both proposed binder composites and traditionally used binder composites were produced and their mechanical and thermal properties tested. The magnesium binders showed promising results as these composites were approximately 2 times stronger having similar density and thermal conductivity. Afterwards the Life cycle assessment (LCA) was carried out to evaluate and compare the environmental impact of all of the tested composites. One of the proposed magnesium binders - magnesium oxychloride cement - showed promising results with bio-based filler, as their combined environmental impact was lower in most categories compared to lime-hemp concrete, and negative CO2 emissions of -37,38 kg CO2/m3 were achieved, which are similar to lime-hemp concrete. These negative CO2 emissions were achieved with biogenic CO2 uptake from hemp growth and low binder content, thus also achieving low thermal conductivity of 0,062 W/m2*K.

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Editorial board of Resources, Conservation & Recycling Journal

29th November, 2017

Dear Editorial board of Resources, Conservation & Recycling,

We would like to submit an Original Research Article “Magnesium binders as an alternative for hemp concrete, comparative study using life cycle assessment” for publishing in the Resources, Conservation & Recycling Journal. Presented article is an original work of the authors and it is not submitted to any other scientific journal.

Presented article deals with the use of magnesium binders for hemp concrete instead of lime binders and their environmental comparison using life cycle assessment (LCA). It generally falls under the following area of your journal -”*Life cycle analysis and management of resources, materials and products to improve resource efficiency and productivity, conserve resources and reduce pollution*”. Lime-hemp concrete have low thermal conductivity and high CO_2 uptake but weak mechanical properties which limits its use low-rise buildings. The novelty of this article is related to the replacement of lime binder with two types of magnesium binders, comparing their mechanical and thermal properties as well as environmental impact by carrying out life cycle assessment of all binder-hemp biocomposites.

The article also touches the area of “*Substitution of primary resources by renewable or regenerative alternatives, including agricultural and forest resources and wastes*” as the proposed materials contains up to 62% agricultural wastes, thus sequestering more CO_2 than is released during their production and causing significantly less environmental impact than traditionally used construction materials.

The abstract contains 234 words and the manuscript – 6928 words (excluding tables), 5 tables and 8 figures

We hope that the members of the editorial board will consider publishing the article in Resources, Conservation & Recycling.

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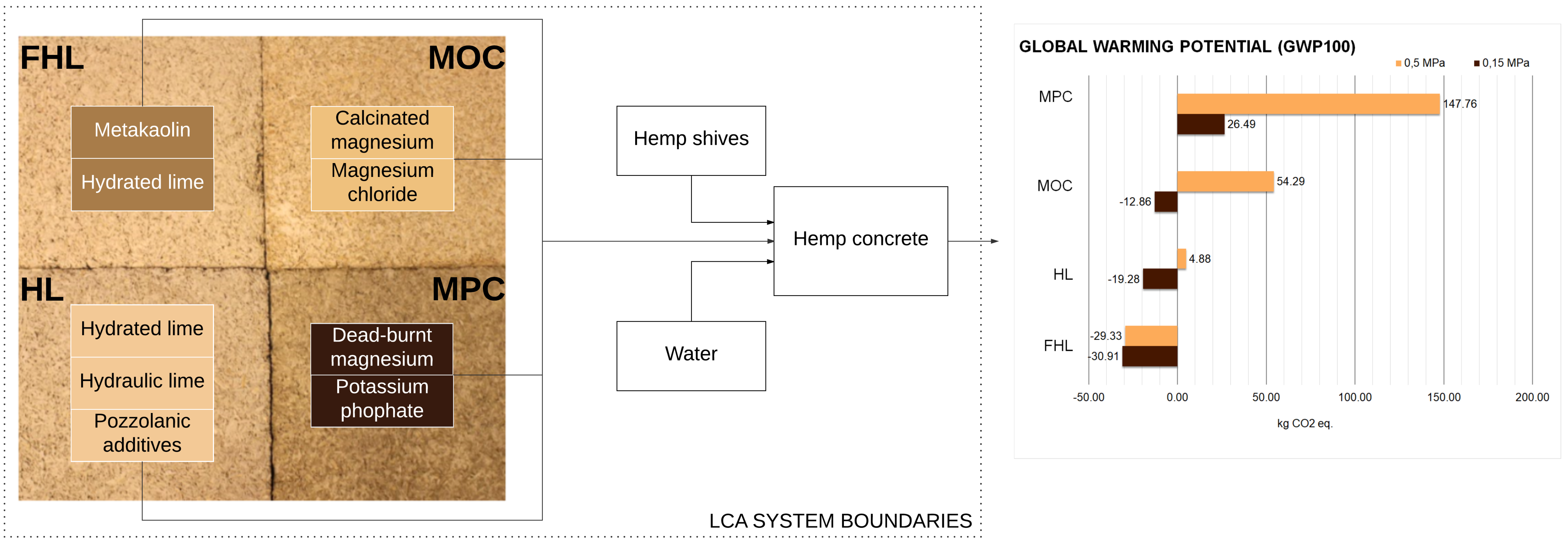
On behalf of all authors,

Yours faithfully,

M.Sc.Ing. Maris Sinka

Graphical Abstract



Magnesium binders as an alternative for hemp concrete, comparative study using life cycle assessment

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Abstract
To counter the negative environmental, particularly, greenhouse gas emission impact generated by the construction industry, many low-impact materials are being produced and researched, having neutral CO_2 emissions and also low thermal conductivity in case of insulation materials. One of these materials is lime-hemp concrete, a self-bearing bio-based insulation material with low thermal conductivity and good CO_2 uptake but with weak mechanical properties. In the present work, alternative magnesium binders are proposed for hemp concrete to substitute the traditionally used lime binder, comparing the environmental impact of these binders with the focus on their global warming potential (GWP). In order to make the comparison, experimental mixtures with both proposed binder composites and traditionally used binder composites were produced and their mechanical and thermal properties tested. The magnesium binders showed promising results as these composites were approximately 2 times stronger having similar density and thermal conductivity. Afterwards the Life cycle assessment (LCA) was carried out to evaluate and compare the environmental impact of all of the tested composites. One of the proposed magnesium binders – magnesium oxychloride cement – showed promising results with bio-based filler, as their combined environmental impact was lower in most categories compared to lime-hemp concrete, and negative CO_2 emissions of -37,38 kg CO_2/m^3 were achieved, which are similar to lime-hemp concrete. These negative CO_2 emissions were achieved with biogenic CO_2 uptake from hemp growth and low binder content, thus also achieving low thermal conductivity of 0,062 $W/m^2{*}K$.

1. Introduction

To reduce the CO_2 emissions in the atmosphere the global community in recent years has signed several agreements committing to limit CO_2 emissions, as for example the Paris Agreement ratified by the EU in 2016 (UN, 2015). To achieve these commitments the EU has set several environmental targets on its own – for example the directive EU2010/31/EU, that has set a goal to reduce the CO_2 emission level by 20% by 2020 (EU, 2010), or the Energy and Climate framework 2030, that aims to reduce greenhouse gases by 40% and improve energy efficiency by 27% by 2030 (EU, 2014). However all this effort does not contribute significantly to reducing the global CO_2 level as it is still on the rise and in 2016 for the first time has permanently exceeded 400 ppm (Betts et al. 2016). So it is clear that additional efforts are needed to achieve the goals set by the global community.

Although the Global Warming Potential (GWP) is currently the most topical environmental impact factor due to the growing consensus that it should be reduced, there are other impact factors which also should be considered in terms of new building materials. It is related to the fact that building material industry can have considerable impact on environment due to significant amount of raw materials consumed; the industry consumes around 3000 Mt/year, more than any other industry (Pacheco-Torgal and Labrincha, 2013). Acidification caused by emissions of SO_2, NO_x, NH_3 and Cl, mostly from combustion of fossil fuels, is also important for construction materials, as they are highly energy intensive. Eutrophication is an enrichment of water with excessive amounts of P and N, resulting in increased growth of aquatic plants that deteriorate the overall quality of the ecosystem; it is not very important with regard to the conventional construction materials. However, it is relevant in terms of bio-based building materials that rely heavily on agricultural residues as eutrophication is closely related with agriculture and use of fertilizers. Abiotic depletion refers to the amount of extracted resources, based on reserves and de-accumulation rates. It is important with regard to the building materials due to the high levels of raw material consumption. Human toxicity and eco-toxicity are other impact factors that concern emissions of toxic substances (Kobetičová and Černý, 2017); however, it is the most difficult category in the terms of modelling as data and inventory are not so advanced as for other categories (Guo, 2012).

Some of the biggest CO_2 emitters are linked to the construction industry (Kylili et al., 2017; Seo et al., 2015), more specifically the energy for heating, ventilation and air conditioning (HVAC) use due to poor building insulation and construction material production (Li et al., 2017; Lin and Liu, 2015). To reduce the negative GWP impact, building materials are needed with both good thermal insulation properties to lower the energy consumption for the household HVAC needs and low carbon footprint in the production process (Palumbo et al., 2015). One of such materials meeting these requirements is the lime-hemp concrete (LHC), a bio-based composite material that contains residues form the hemp production – hemp shives as porous organic filler and hydrated or hydraulic lime as binder. During its growth hemp has taken up CO_2 through photosynthesis and lime is sequestering CO_2 by hardening through carbonation, and as a result the ultimate material is carbon neutral or even negative (Ip and Miller, 2012; Pretot et al., 2014; Shea et al., 2012). The material also has good thermal insulation properties (Walker et al., 2014), exceptional moisture buffering (Maalouf et al., 2014; Rahim et al., 2015) and acoustic properties (Cérézo, 2005).

Regarding issues related to the GWP, data about lime-hemp concrete carbon sequestration varies because of the different mixtures used – 6.67 kg CO_2 eq./m^3 (Pretot et al., 2014), 48.36 kg CO_2 eq./m^3 (Arrigoni et al., 2017), 120.26 kg CO_2 eq./m^3 (Ip and Miller, 2012), 136.65 kg CO_2 eq./m^3 (Boutin et al., 2006) but all of them show that it is possible to obtain material that is CO_2 negative. The LHC materials have also shown good properties with regard to other impact categories described above, compared with traditionally used bricks or concrete blocks with mineral wool insulation, as the LHC in most categories (e.g. acidification and toxicity) shows lower or similar impact (Pretot et al., 2014), mostly due to lower amounts of highly energy intensive materials, such as cement or burnt clay bricks.

LHC materials use hydrated and hydraulic lime as a binder, which has relatively low mechanical strength that in combination with large volumes of organic hemp filler limits the LHC use to in-situ filling of load bearing structural frames (Latif et al., 2014), or to use it in panel or building block production with increased binder amount, even though without load bearing capabilities. The lime in LHC is also influenced by the biological retarders emitted by hemp shives during the curing, thus leading to reduction of early and overall strength of the material (Balciunas et al., 2015).

One of the materials that can be used to substitute lime in the LHC materials and increase their strength is magnesium-based binders. These binders are usually used in combination with various bio-based fillers such as wood (Plekhanova et al., 2007; Smakosz and Tejchman, 2014; Zhou and Li, 2012), rape stalk (Ning and Bing, 2016), other agricultural residues (Amiandamhen et al., 2016), wood pulp (Donahue and Aro, 2010), and also hemp (Del Valle-Zermeño et al., 2016). The advantage of magnesium binder lies in its considerably greater compatibility with organic fillers(Zhou and Li, 2012) in contrast with calcium binders that creates an alkaline environment in the mixing process in which lignin and other organic compounds are released from bio-based materials, thus retarding the setting of cement or lime (Diquelou et al., 2015).

Magnesium binders have two major hardening mechanisms that are relevant in the scope of bio-based materials, they differ in the compounds added to mixture, the necessary hardening conditions, and the end properties of the material – magnesium oxychloride cement and magnesium phosphate cement. Although these binders are not new, they have been studied relatively little comparing to cement or lime.

Magnesium oxychloride cement (MOC), commonly known as Sorel cement, was discovered 150 years ago, shortly after discovery of Portland cement (Li et al., 2013) and it is non-hydraulic. It is produced by combining magnesium oxide with magnesium chloride water solution, forming a $MgO–MgCl_2–H_2O$ ternary system (Xu et al., 2016). In the reaction of MgO with $MgCl_2$, 4 main crystal reaction phases are created, two of which can stably exist in temperatures below 100 ^{0}C, namely phase 3 ($3Mg(OH)_2·MgCl_2·8H_2O$) and phase 5 ($5Mg(OH)_2·MgCl_2·8H_2O$) (Xu et al., 2016). This type of MgO binder has high early strength, and can reach compressive strength of 120 (Li et al., 2013) to 140 MPa (Xu et al., 2016). A low calcination temperature (about 700 ^{0}C) produces the most reactive MgO, which consumes less energy compared with the dead-burned magnesium oxide. As all magnesium oxide reacts with magnesium chloride, no CO_2 can be absorbed through carbonation.

Nowadays this cement is typically used to produce magnesia based sheeting boards containing wood fiber and perlite and are covered with glass cloth. They can be covered by a magnesium phosphate layer for moisture resistance, and are mostly used for their superior fire resistance, as well as strength and microbiological resistance.

Magnesium phosphate cement (MPC) – a type of chemically bound ceramics - used in this study is based on monopotassium phosphate (KH_2PO_4) reaction with dead-burned magnesium oxide, calcined at temperatures above 1500 ^{0}C to lower its reactivity and specific surface. The reaction of MgO and monopotassium phosphate forms the crystalline structure $MgKPO_4\,6H_2O$ (Le Rouzic et al., 2017), titled K-struvite or ceramicrete (Del Valle-Zermeño et al., 2016). It has high compressive strength of 80 MPa and more (Zhang et al., 2017) and very fast setting time, that can lead up to 80 % compressive strength at 3 h compared to 28 days (Ma and Chen, 2017). Most commonly it is used as a repair mortar due to its fast setting, high early strength and durability. Nowadays the monopotassium phosphate has replaced the monoammonium phosphate that generated ammonia in hardening process contributing to creation of pores within the set binder, thus not only reducing thermal conductivity of the binder (Ma and Chen 2017) but also creating an unpleasant odor in the process (Ma et al., 2014).

MPC can be used with different organic aggregates (Donahue and Aro, 2010) to create wall panels (Amiandamhen et al., 2016), with porous organic aggregates (rape stalk and hemp shives) to create insulation panels (Ning and Bing, 2016)(Del Valle-Zermeño et al. 2016). Both magnesium binders are a good alternative for traditionally used cement and lime binders because of their high early strength, and fire resistance and compatibility with organic aggregates.

The goal of the research is to compare bio-based materials with different binders – lime and magnesium based – from the environmental impact perspective. To achieve this, it is necessary to use Life cycle assessment (LCA) for calculating both negative and positive environmental impacts of chosen binders. In order to do the calculation a functional unit that is comparable for all the binders is necessary. For this purpose experimental part of this paper is focused on finding key properties of proposed biocomposites by creating experimental hemp-binder mixtures and testing them.

A functional unit is defined as a $1m^2$ of wall with defined U value of 0.18 W/m^2*K that is a normative requirement for wall thermal transmittance in Latvia. This thermal transmittance is to be achieved with lowest possible amount of binder that will be found experimentally in this paper. The limits of compressive strength of the bio-composite functional unit will be set at a minimum value of 0.15 MPa according to the EN 996, to ensure self-bearing capabilities and of 0.5 MPa to be used as non-load bearing blocks (Sinka et al., 2015).

SimaPro life cycle assessment software and the Ecoinvent 2.0 database (Frischknecht et al., 2005) will be used in the LCA for majority of the processes, for the processes that are not included in the Ecoinvent database an existing processes will be used with some changes. Analysis will be done according to a problem oriented method – the CML 2 baseline.

Tab. 1: Composition and properties of materials used

Name	Classification	MgO	CaO	SiO_2	Fe_2O_3	Al_2O_3	Size distribution	Calcination temperature	Binder
RKMH-F	Caustic magnesia	73.0%	4.0%	4.0%	3.0%	1.0%	90% < 30 µm	750 ^{0}C	MOC
M-76	Dead-burned magnesia	81.0%	11.0%	2.0%	8.0%	0.3%	0 to 0.2 mm	1700 ^{0}C	MPC
MK	Metakaolin	0.1%	0.1%	51.8%	0.5%	34.2%	Avg. 0.7 µm	850 ^{0}C	FHL
Name	**Fiber**	**>20mm**	**10-20mm**	**0.63-10mm**	**Dust**	**Density**	**Thermal cond.**	**Moisture**	**-**
Hemp shives	1.7%	0.5%	3.7%	92.0%	2.2%	108.36 kg/m^3	58.07 W/m*K	11.75%	-

2. Materials and methods

2.1. Materials

In this research, two different types of magnesium oxides were used – caustic and dead-burned magnesia, both types being made by calcination of magnesite ($MgCO_3$). Both types are produced in Europe. The dead-burned type by the name M-76 comes from Slovakian company "Integra Ltd", and it is calcined at temperatures up to 1700 ^{0}C, used for MPC binder. Caustic magnesia by the name CCM RKMH-F is provided from the Austrian company "RHI AG Ltd", used for MOC binder. Their composition is presented in Table 1.

For hardening of dead-burned magnesia a monopotassium phosphate KH_2PO_4 fertilizer (MKP) 0-52-35 supplied by Prayon S.A. was used, with P_2O_5 content at least 51.6%. Magnesium chloride hexahydrate made in Germany and containing 47% $MgCl_2$ was used; in mixtures (Table 2) it is used as brine solution (1:1 salt:water by weight).

In this research two types of lime were used. Hydrated lime CL90, made by Lhoist Poland Ltd used for experimentally formulated lime binder FHL and hydraulic lime binder used commercially for the LHC construction, containing 70% hydrated lime, 20% hydraulic lime and 10% additives - HL.

Metakaolin containing waste products that were used in this research are the by-products from porous glass granulate production process (Stikalporas Ltd., Lithuania), used for FHL binder. In producing porous glass granulate, kaolin clay is used as anti-agglomeration agent for glass granulate during its formation. As a result, when the glass is melted and granulated, the kaolin clay is also calcined at 800-850 ^{0}C temperature for 40-50 minutes. The produced metakaolin cannot be reused for the production process, so it is considered as a by-product or waste product. According to the SEM and the XRD analysis the obtained metakaolin is very similar to the commercially available one that makes it appropriate for products with aim to lower environmental impact. The specific surface of metakaolin is 15.86 m^2/g. (Bumanis et al., 2017)

Hemp shives were obtained from local grower and producer "z/s Rudeņi". Main properties of hemp shives can be seen in Table 1. In previous experiments this type of shives has proven to have the best granulometric composition to achieve both high compressive strength and low thermal conductivity (Sinka et al., 2015).

Figure 1 FHL – left top, HL – left bottom, MOC – right top, MPC – right bottom

Tab. 2: Mixtures of biocomposite samples, mass ratio

Binder type	Name	Binder	Water for binder	Hemp shives	Water for shives
MPC	MPC1	2.30	1.00	1	1.25
	MPC2	1.80	0.80	1	1.25
	MPC3	0.90	0.40	1	1.25
	MPC4	0.60	0.27	1	1.25
MOC	MOC1	2.50	-	1	1.25
	MOC2	1.75	-	1	1.25
	MOC3	1.25	-	1	1.25
	MOC4	0.84	0.34	1	1.25
FHL	FHL1	2.50	1.25	1	1.25
	FHL2	2.00	1.00	1	1.25
	FHL3	1.00	0.50	1	1.25
	FHL4	0.75	0.38	1	1.25
HL	HL1	2.50	1.25	1	1.25
	HL2	2.00	1.00	1	1.25
	HL3	1.00	0.50	1	1.25
	HL4	0.75	0.38	1	1.25

2.2. Mixtures

Mixtures of samples can be seen in Table 2, ratio is given by mass. In total four different binders were chosen (Fig.1.):

MPC – magnesium phosphate cement – dead burnt MgO to KH_2PO_4 ratio by mass 1.25:1
MOC - magnesium oxychloride cement – caustic MgO to $MgCl_2$ brine (1:1) ratio by mass 1.5:1
FHL - experimentally formulated lime binder – hydrated lime CL90 to metakaolin ratio by mass 1.5:1
HL – commercial hydraulic lime binder - hydrated lime to hydraulic lime to pozzolanic additives ratio by mass 7:2:1

Specified mixtures were chosen to represent the wide range of possible hemp biocomposite binders. HL represents the traditionally used binder, with its composition similar to many binders commercially used in hemp construction (Ip and Miller, 2012), as it contains 70% hydrated lime with 20% hydraulic lime. FHL represents an alternative hemp binder with industrial by-products as pozzolanic admixtures thus severely reducing the environmental impact. MPC and MOC binders are chosen as an alternative to conventional lime-based binders for hemp concrete with prospect of reduced environmental impact.

The amount of shives used was constant in all mixtures, density was regulated only by quantity of binder and 4 different compositions were tested for each binder. Water was used to pre-treat the shives at the weight ratio of 1:1.25 shives/water, in order not to deprive the binder from the necessary amount of water.

The amount of binder was determined to achieve the desired compressive strengths – 0.15 and of 0.5 MPa. The ratio of binder: hardener was retained from previous experimental work, choosing the ratios with the highest compressive strength. The used FHL ratio 1.5:1 lime to metakaolin was also found to be the most suitable in the previous research.

2.3. Preparation of samples

The biocomposites were mixed in a forced action double shaft laboratory mixer BHS DKX 0.06, with the mixing speed of 60 rpm in 4 stages:

1. *Premixing of shives* – hemp shives are premixed with set amount of water (1:1.25 by weight, see 3.2.), hemp shives

are hydrophilic and need to be premixed with water in order not to deprive the binder from water that is needed for hydratation process, the mixing is done for 1 minute.

2. *Premixing of binder* - prior to addition to shives, the binder is premixed with all the additives in a dry state manually.
3. *Addition of binder* - the binder is added to the shives, then the rest of the water or $MgCl_2$ solution is poured in the mixer and the mixing continued for 2 minutes, the whole operation is 3 minutes long. The mixture proportions are displayed in Table 2.
4. *After mixing* - the samples were moulded in custom sized plywood moulds. Demoulding was done after 2 days. Afterwards samples were cured in laboratory conditions (20±2 ^{0}C and 40±10 %RH) for approximately 28 days, until weight equilibrium was achieved.

2.4. Testing

Thermal conductivity of biocomposites was tested after curing had finished. It was recorded with a heat flow meter LaserComp FOX600, complying with the LVS EN 12667 standard guidelines. The settings of the test were 0 ^{0}C at the upper and 20 ^{0}C at the lower plate. After thermal conductivity measurements, compressive strength of the biocomposites was tested. Samples were produced by sawing the samples in 100*100*(80 - 93) mm specimens. According to the LVS EN 826, compressive strength was measured at 10 % relative deformations. The Zwick Z100 universal testing machine was used to conduct the tests, the force was applied with 10 mm/min speed.

2.5. Life cycle assessment

Life cycle assessment has been done according to the ISO 14040 consisting of the following steps:

1. Definition of goal and scope;
2. Inventory analysis;
3. Impact analysis;
4. Interpretation.

2.5.1. Definition of goal and scope

The goal of the study is to use LCA to assess environmental impact with focus on GWP, of the new type of construction material – magnesium-hemp concrete in comparison to lime-hemp concrete. As LHC has proven in previous studies to have low environmental impact, especially GWP (Boutin et al., 2006; Ip and Miller, 2012), it is proposed that magnesium based biocomposites could have even less environmental impact due to smaller amounts of binder necessary and lower calcination temperature of magnesium.

Within the scope of the study, data from the results of experimental part will be used to create functional units and necessary amount of used raw materials. The Sima Pro 7 LCA software together with the Ecoinvent 2.0 (Frischknecht et al., 2005) database is used in the study.

To compare the results of LCA for all the different mixtures used, a functional unit is required with comparable properties for all the samples. Within the scope of this research two functional units is used. The first unit with lower compressive strength of 0.15 MPa represents the traditional construction method of hemp biocomposites – in-situ placement using formwork. The second unit with higher strength of 0.5 MPa represents its use as the non-load bearing construction blocks. As LHC materials are primarily used as wall insulation material, a functional unit of 1 m^2 of wall is chosen, similar to other studies in this field (Pretot et al., 2014)(Ip and Miller, 2012). The wall thickness is varied in correlation with thermal conductivity and compressive strength found during the experimental phase, the wall thickness is adjusted to match the necessary U-value of 0.18 W/m^2*K which is a normative requirement for walls in Latvia. The summary is presented in Table 4.

In this study the allocation principle is applied for hemp shives and metakaolin which are both by-products of their respective industries. Thus economical allocation is used, as mass allocation would not represent the correct relations between primary products and by-products. In both cases it is because the mass of primary products are significantly lower than that of by-products, although the primary products generates 75 – 95% of the income. In such cases economic allocation is preferred (Ardente and Cellura, 2012). The impacts are assessed with the problem oriented CML 2 baseline (Guinée, 2002) method.

As the functional unit defines materials to have uniform U-values and no reliable data regarding maintenance of such materials is available, the use phase for all materials is considered to be equal and is not taken into account for assessment. The end-of-life phase is also not calculated within the scope of this study, as the system boundary corresponds to assembly of materials at the construction site – as seen in flow chart in Figure 3 it is “cradle-to-gate” system with accounting for bio-based carbon storage (Pawelzik et al., 2013).

2.5.2. Inventory analysis

The data used in this study are gathered from several sources. Where available and applicable the Econivent database is used, for the rest of the data similar studies, reports or personal communications are used and summarized below.

Hemp

To take into account impacts of hemp growing and production, mainly data representing the situation in Latvia were used and compared with similar studies. These data have been acquired mainly from research work done by V. Stramkale at Latgale Agriculture Research Centre (V. Stramkale 2012; Veneranda Stramkale 2015), with additional information from communication with the largest regional hemp growers and processers. The main data related to the hemp impact regard amount of fertilizer used

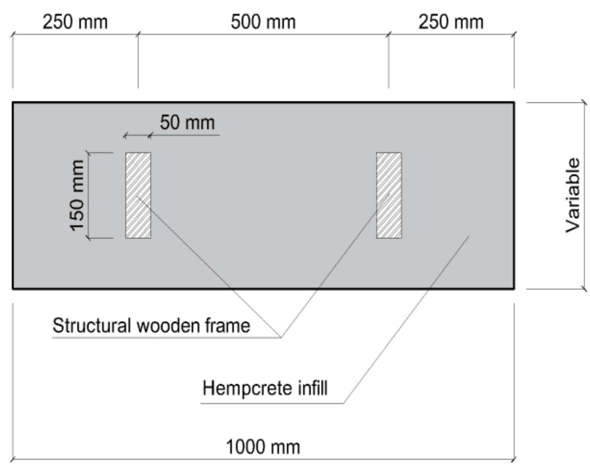


Figure 2 Functional unit of wall section

and crops harvested, as these present the highest impact values and are more region dependent (Turunen and van der Werf, 2006), the amount of machinery used or fuel consumed has less impact and is less region dependent.

As the majority of hemp in Latvia is grown for fiber and not for oil, only this type of hemp growing and processing is reviewed. Hemp is usually used as rotational crop after various grain crops. Any particular land cultivation after the previous crops is not included in this study as it varies among crops, it starts with the plowing of the field, followed by cultivation, then lime treatment (every 3 years) and application of fertilizer two times, applying nitrogen separately from phosphate and potassium.

For the soil of average fertility the following annual fertilizer treatment is required: 80 kg of N, 70 kg of P_2O_5 and 147 kg of K_2O per hectare. Lime treatment is required every 3 years with 360 kg/ha respectively. Seeding rate of 50 kg/ha is optimum for hemp growing for fiber (V. Stramkale 2012). Seed production is taken into account, based on the Ecoinvent database of rapeseed production with additional transportation of 2000 km by sea and 200 km by road.

No treatment with pesticides or herbicides is necessary for hemp (González-García et al., 2010). All farm machinery used in the above mentioned operations is split in three groups depending on the allocated group emissions – A tractors, B mowers/harvesters, C the rest of the equipment. Hemp is harvested in fall, it is mowed and laid in parallel lines.

According to research and farmer experience, one of the most productive varieties in Latvian conditions is a variety Bialobrezskie (V. Stramkale 2012; V. Stramkale 2015) developed in Poland. Its average yield in good conditions amounts to 16500 kg/ha of straw.

The emissions associated with fertilizer production are calculated using the Ecoinvent database, however the emissions from application and leaching of the fertilizer should be accounted for separately. Emissions to water are Nitrates (NO_3) – 40 kg/ha by leaching and Phosphates (PO_4) – 0.01 kg per kg of the P applied. Emissions to air are Ammonia (NH_3) – 0.02 kg per kg of nitrogen applied, nitrous oxide (N_2O) – 0.0125 kg per kg of nitrogen applied from direct emission from soil and 0.01 kg per NH_3 emitted and 0.025 kg per NO_3 emitted, nitrogen oxides (NO_x) – 10 % of N_2O emissions (Turunen and van der Werf, 2006)(Pretot et al., 2014). Heavy metal emissions are taken from a hemp fiber LCA study (Turunen and van der Werf, 2006), which uses the balance approach, and the reference is based on wheat crop that yields 6800 kg/ha of grain with 0.1 mg/kg of Cd, 5.9 mg/kg of Cr, 0.22 mg/kg of Ni, 0.2 mg/kg of Pb.

After mowing of the hemp stalks, they are laid in parallel lines and dried. In order to obtain long fibers, stalks are soaked and retted on field, redried and compressed in bales. Using a front loader tractor, bales are loaded onto lorries and transported over an average distance of 40 km.

All further processing is done on automated fiber processing lines. Stalks are crushed and fibers separated from shives, and dust is also removed. The whole process consumes 112 kWh of electricity to process 1 t of hemp stalks. Electricity is supplied by the public grid. Three different products are obtained after processing. Fiber is the main product of the whole process. Growing of the hemp is based on this product, as it is the most important in economic sense, hemp shives and dust being the by-products. After processing of stalks the hemp fiber is delivered for further transformation into textiles that is not taken in account in calculations, as well as the dust, which is transformed in briquettes for heat energy. Impact factors are presented according to economic allocation, as the mass does not display the correct importance ratio between the products, as discussed in 3.2.1.

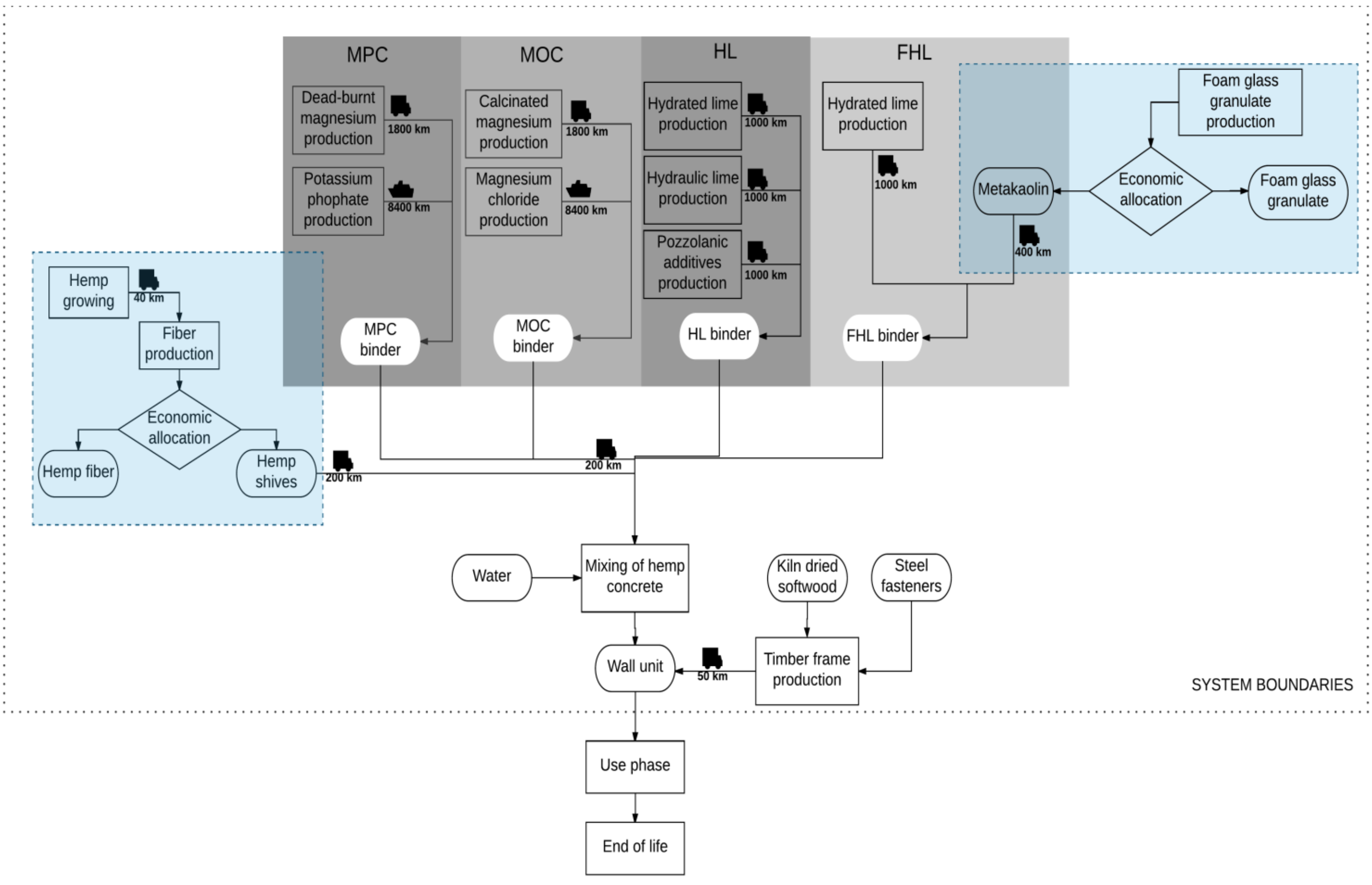


Figure 3 Flow chart of hemp-binder biocomposite production

During the hemp growing CO_2 is sequestered and stored by photosynthesis. As this CO_2 is locked into the LHC wall for its lifespan, it contributes as a negative CO_2 emission. For every kg of hemp stalk 1.84 kg of CO_2 is absorbed.

Lime binders

For lime based binders, hydrated lime is used as a primary component, with the highest possible level of purity (90 % or more CaO). During calcination of calcium carbonate, CO_2 is emitted from two sources – from burning of fuel needed for calcination, and from calcium carbonate decomposing in CaO and CO_2. After lime is hydrated and used as a binder, it hardens by absorbing CO_2 and forms $CaCO_3$, thus sequestering all the carbon dioxide that was released from $CaCO_3$ in the carbonation process – 594 g of CO_2 per kg of $Ca(OH)_2$ (Pretot et al., 2014).

Hydraulic binder HL is provided by a local LHC producer who uses special made binder mix consisting of 70% hydrated lime CL90, 20% hydraulic lime NHL5 and 10% pozzolanic additives. As these pozzolanic additives are not known, in the LCA they are replaced with cement to represent the worst case scenario. As portlandite carbonates are present only in hydraulic lime, it is assumed that the content of portlandite in hydraulic lime is 60% (Pretot et al., 2014) which captures 356.4 g of CO_2 per kg of hydraulic lime. Transportation for hydraulic and hydrated lime is assumed to be 1000 km, which is the average distance to Latvia from most of the factories in Poland that supply commercially viable hydrated and hydraulic lime.

The experimental binder consists of 60% hydrated lime and 40% metakaolin. The metakaolin as a by-product of foam glass granulate production is used to lower the impact on the environment. Emissions are allocated economically, 2% of glass granulate emissions are allocated to metakaolin. Transportation distance is calculated to be 400 km from the plant in Lithuania(Fig.3.).

Magnesium binders

For caustic magnesium oxide a process from Ecoinvent database is used. On the other hand as data about LCA of dead-burnt MgO is not available, an existing unit process of magnesium oxide production from the Ecoinvent database is used and updated. Dead-burnt magnesia can be produced form the same $MgCO_3$ as the regular magnesium oxide, requiring only calcination at higher temperatures. Within the scope of this study a temperature of 1500 ^0C for 5 h has been chosen. When reactive MgO is produced, the $MgCO_3$ is burned at 750 ^0C, thus use of the temperature difference and specific heat capacity of MgO makes it possible to calculate the heat amount necessary to heat 1 kg of MgO for 750 ^0C – 0.6555 MJ. As the kilns operate with heat loses, a 37 % heat loss is calculated according to research on dead burned magnesia kiln heat loses (Chakrabarti, 2002), which delivers 0.898 MJ of extra energy for every kg of dead burned MgO. For both magnesium oxides 1800 km land transportation is calculated(Fig.3.).

The used monopotassium phosphate (MKP) is Praton produced 0-52-35 fertilizer, for LCA the P values are taken from monoammonium phosphate Ecoinvent process, emissions associated with ammonia is removed and replaced with input of 0.508 kg potassium carbonate and 0.1617 kg of fossil CO_2 emissions per kg of MKP, as production from potassium carbonate reaction with phosphoric acid are most commonly used (Kent, 2013).

The magnesium chloride used is Germany produced magnesium chloride hexahydrate ($MgCl_2 \cdot 6H_2O$), with the $MgCl_2$ content of 47 %; for the LCA a unit process of sodium chloride extracted from brines similarly to $MgCl_2$ is used. For both monopotassium phosphate and magnesium chloride 8400 km sea transportation is calculated.

Tab. 3: Results of biocomposite tests

Binder type	Name	Density	Compressive strength, MPa	Thermal conductivity
MPC	MPC1	414,86	0,823	0,087
	MPC2	359,25	0,409	0,078
	MPC3	249,81	0,157	0,062
	MPC4	211,16	0,098	0,057
MOC	MOC1	416,18	0,709	0,092
	MOC2	357,14	0,367	0,081
	MOC3	252,79	0,200	0,072
	MOC4	214,34	0,155	0,063
FHL	FHL1	488,63	0,435	0,103
	FHL2	352,54	0,111	0,079
	FHL3	265,81	0,071	0,064
	FHL4	223,35	0,062	0,062
HL	HL1	459,60	0,570	0,101
	HL2	391,40	0,204	0,081
	HL3	265,32	0,105	0,069
	HL4	220,90	0,071	0,063

Structural frame and assembly

The functional unit not only contains LHC or MHC, but also the load-bearing timber frame, as the material itself lacks the necessary structural capabilities. It is comprised of two 150x50 wooden beams placed at a distance of 500 mm and centered (Fig. 2). In the LCA, a full production cycle of a wooden frame is considered, including CO_2 absorbed during the growth of the trees. A 5 kg of steel fastening for every 1 m^3 of frame is also included. No extra inner or outer finishing is used for easier comparison of the materials, as there are many different alternatives that can be chosen.

There are different ways of producing the hemp based materials – in-situ, spraying, building blocks or prefabricated panels. Within this research both functional units will be treated as in-situ. To account for this manufacturing method electricity required for use of a mixer is included, 4 kWh per 1 m^3 of hemp biocomposite (Ip and Miller, 2012).

As regards the transportation, it is assumed that 200 km are required for binder and hemp materials from the material distribution area to the construction site. For wooden frame 50 km are assumed to account for more locally available distribution places. The functional unit needs to take into account all the extra transportation and material assembly for it to be comparable with similar studies and to measure the overall impact of LHC and MHC materials. Transportation of materials to distribution site is taken into account in the previously described processes.

3. Results

3.1. Compressive strength and thermal conductivity of experimental mixtures

In the first part of the research experimental mixtures of various LHC and MHC biocomposites were made and tested. The result summary can be seen in Table 3. For all binder types the mixtures were chosen to achieve compressive strength values so that 0.15 and 0.5 MPa fall in the achieved strength range. This was

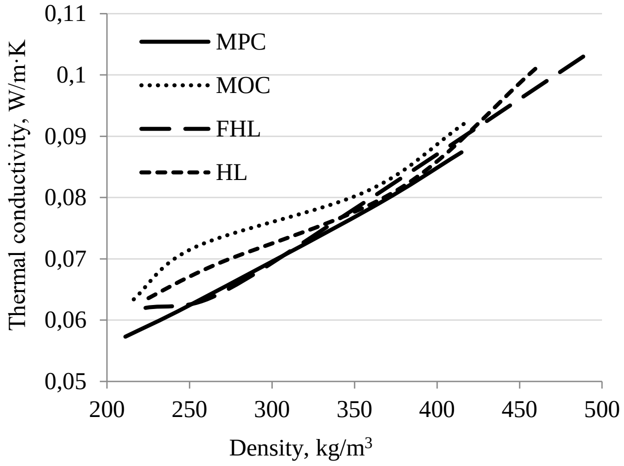


Figure 4 Density/thermal conductivity ratio of biocomposites

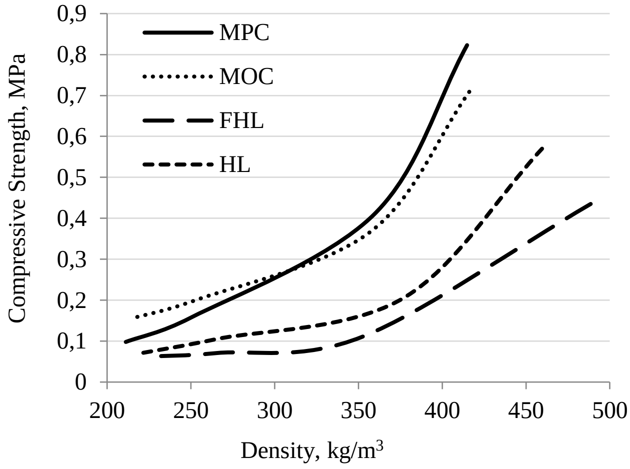


Figure 5 Density/compressive strength ratio of biocomposites

accomplished in all mixtures, except for minimal shortage in FHL case of 0,43 MPa.

When results are viewed in terms of density:thermal conductivity (Figure 4), it is observed that MOC has the highest ratio, MPC has the lowest one and the lime-based samples fall in between, e.g. MOC 0.081, FHL 0.079 and MPC 0.076 W/m*K at around 350 kg/m^3 density. The ratio of FHL and other lime-based binders correspond to the results of previous tests, MOC's higher ratio is due to its higher compressive strength at similar densities, as it has been found out in previous tests confirming that biocomposites with lower compressive strength and lower inner core shives-binder adhesion have lower thermal conductivity (Sinka et al., 2015). Lower thermal conductivity of the MPC can be attributed to surface area of the dead-burnt magnesia that have positive influence on the thermal conductivity as the volume of binder is lower compared to the composites with similar density.

In the Figure 5 it can be seen that both magnesium binder composites have significantly higher compressive strength to density ratio than lime-based composites, similarly to the Figure 6, with the ratio of compressive strength and thermal conductivity. Therefore it can be concluded that MOC and MPC have the lowest ratio. This was expected as in previous tests both MOC and MPC 2:1 sand:binder mortars showed 3 to 4 times higher compressive strength compared to lime-based ones, e.g. 37.50 MPa for MOC and 13.72 for HL. It must be noted that the compressive strength achieved with MOC and MPC mortars was 2 to 3 times lower than has been achieved in different studies (Li et al., 2013)(Xu et al., 2016; Zhang et al., 2017), which is explained by use of lower class MgO binders with lower amount of free MgO in this research. This leaves the possibility for future improvement in the area of MOC and MPC biocomposite strength.

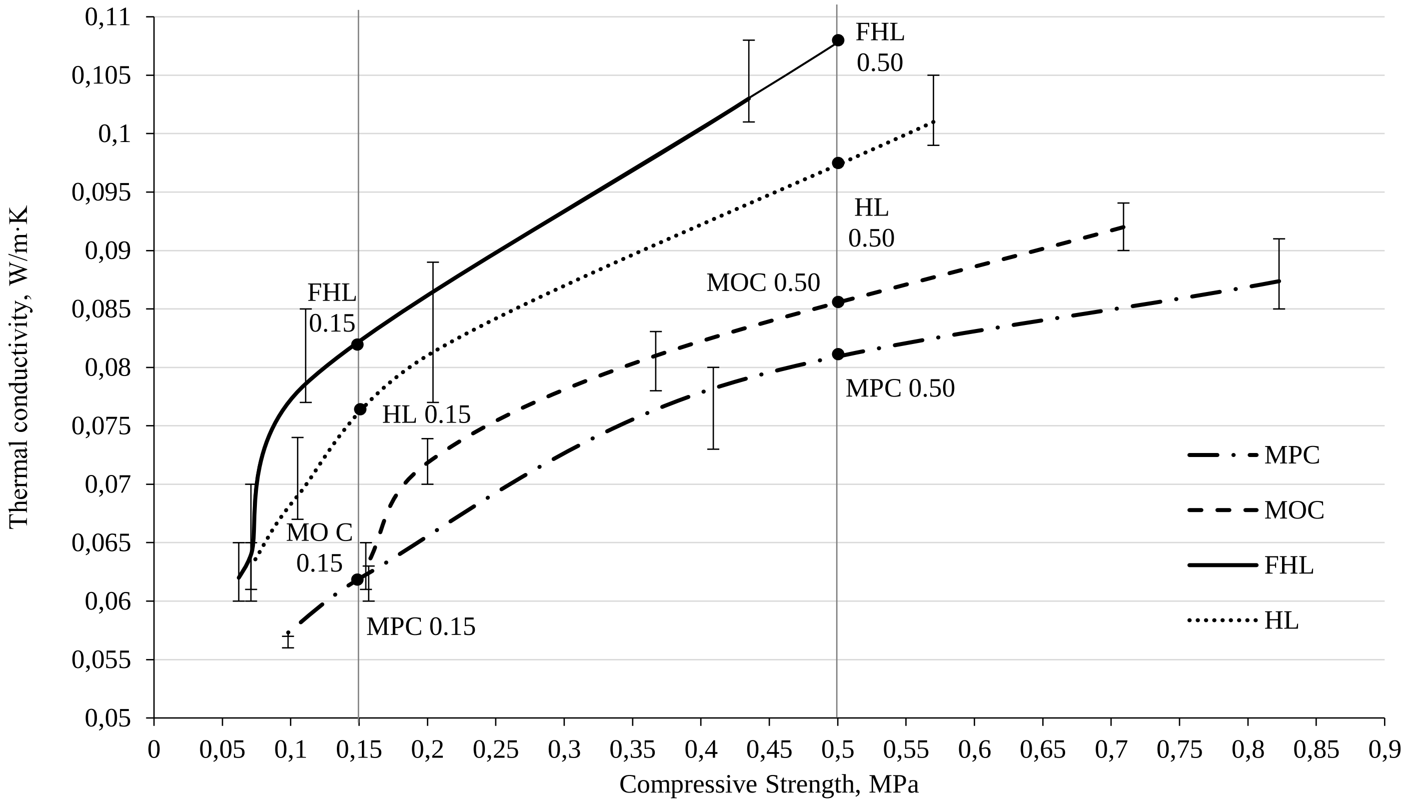
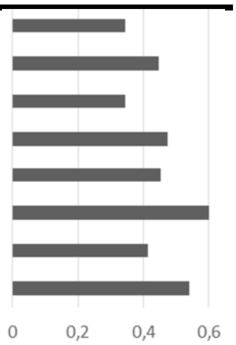


Figure 6 Compressive strength/thermal conductivity ratio of biocomposites

Tab.4. Properties of functional unit and materials used

Binder type	Name	Shives, kg	Water, kg	Binder, kg	Compressive strength, MPa	Thermal conductivity, W/m*K	Density, kg/m^3	Thickness at U=0,18 W/m^2*K, m	FU at U=0,18 W/m^2*K, relative thickness, m
MPC	MPC(0,15)	125,6	205,2	108,5	0,15	0,062	245,2	0,344	
	MPC(0,50)	125,6	268,5	239,7	0,5	0,080	371,5	0,446	
MOC	MOC(0,15)	125,6	157,0	98,8	0,15	0,062	210,1	0,344	
	MOC(0,50)	125,6	157,0	256,4	0,5	0,085	380,1	0,474	
FHL	FHL(0,15)	125,6	286,4	258,7	0,15	0,082	368,9	0,453	
	FHL(0,50)	125,6	320,3	326,5	0,5	0,108	515,9	0,600	
HL	HL(0,15)	125,6	248,3	182,7	0,15	0,075	322,6	0,415	
	HL(0,50)	125,6	308,0	302	0,5	0,097	446,6	0,541	



The graph also shows that all lime-based binders have higher thermal conductivity as magnesium binders at similar strength due to the higher density necessary to achieve this strength. There are two main issues causing lower strength of the lime binders. First, the compressive strength of lime-based mortars is lower than that of magnesium-based ones. Second, there are compatibility issues as during curing the lime binders create highly alkaline environment, which enables the bio-based hemp filler to release lignin, as well as other compounds, that lower the overall compressive strength (Diquelou et al., 2015). MgO binders do not encounter this problem as MgO provides lower alkalinity and better biocompatibility (Zhou and Li, 2012).

3.2. Life cycle impact assessment and interpretation

Two functional units of the obtained results are calculated for all binders. As none of the experimental values are either 0.15 or 0.5 MPa, the necessary data is obtained by interpolation or extrapolation (Table 4). For the LCA input values, the amount of raw materials is converted to the amount required for 1 m^3 of material, thermal conductivity and density is calculated from results of the experimental part.

As it can be seen in Table 4, due to the lowest conductivity:strength ratio MPC has the lowest required thickness; however, MOC has the lowest density thus leading to lower raw material consumption. Lime-based binders have similar thickness and density, with HL being slightly superior with lower thickness and density.

Results from the CML 2 baseline method are summarized in Fig. 7 for both functional units. Individual impact assessment for each category of four main 0.15 MPa wall types can be seen in Fig. 8. Analysis of Fig. 7 shows that MPC has the highest impact in almost all categories, except for the Ozone layer depletion and the Fresh water aquatic ecotoxicity, although the score in both of these is also high. It is also the only binder that has positive CO_2 emission, all other composites exhibiting CO_2 sequestration. As to the impact categories of acidification and eutrophication, the MPC has 5 to 10 times higher impact than all other binders, it being 2 to 3 times higher in other categories. These data together with Fig. 8 permit to conclude that the highest impact is caused by monopotassium phosphate, as it leads in almost all the categories, particularly in acidification and eutrophication. When viewed in detail it was found that most of monopotassium phosphate impact is caused by wet-process phosphoric acid production.

Magnesium oxide causes significant impact on the Fresh water aquatic ecotoxicity, Marine aquatic ecotoxicity and GWP 100. In comparing the dead-burned MgO to low temperature calcined MgO it was calculated that the extra heating produces only 0.08 kg/CO_2 eq., as it requires around 1 MJ of extra energy. This small increase reflects minor difference between GWP 100 impact of MPC and MOC. Comparison of both wall types allows to conclude that, although MPC has the lowest density and thermal conductivity at 0.5 MPa, it is achieved by significant increase in amount of phosphate, which in turn leads to even higher impact compared with other types of binders. It can be suggested that trials of biocomposites with lower amount of phosphate should be made, as it is the main problem of the MPC composite as far as the LCA is concerned. Although it is likely that lower phosphate amounts should result in lower compressive strength.

As can be observed in Fig. 8 the hemp shives contribute significantly to almost all binder categories, because 0.15 MPa biocomposites are comprised of 30 to 50 % hemp shives. More in depth analysis leads to conclusion that most of the emissions associated with hemp comes from 3 major groups of fertilizers used and their leaching (ammonium nitrate, potassium chloride and triple superphosphate), as well as diesel for farm machinery and electricity for processing lines. As not all of the fertilizers are used efficiently it is suggested that this amount could be reduced by using more efficient farming technologies (Turunen and van der Werf, 2006). Hemp also contributes to the largest amount of CO_2 sequestration, as hemp stalks have absorbed CO_2 during their growth phase. Allocation is needed as 3 different products are produced by processing the hemp stalks. As the product weight does not reflect their value relationship, the economical allocation is used, that also contributes to lowering CO_2 sequestration of hemp, as dry hemp stalks consist of 54 % hemp shives, but according to economical allocation only 27 % of emissions and CO_2 absorption can be allocated. This should be taken into account if data of this research is used in cases of different fiber/shives economical relationship.

Comparing HL and FHL emissions from Fig. 7 allows to see that the results do not differ by more than 15 % in all the impact categories except GWP. This is due to the fact that both binders are heavily based on hydrated lime. The only significant difference is in GWP 100 category for both wall types because of the low CO_2 emissions associated with metakaolin production as it is a byproduct of foam glass granulate production. If in this position purposefully made metakaolin or other pozzolans would be used instead, FHL impacts would be significantly higher and could not be justified from environmental point of view.

Analysis of MOC from data in Fig. 7 shows that compared with other biocomposites in cases of same impact categories, such as adiabatic depletion, acidification, eutrophication, ozone layer depletion and photochemical oxidation, it has lower values for the 0.15 MPa wall, although this changes with the 0.5 MPa wall. The high strength/density ratio is credited for lower impact, as well as magnesium chloride that is used as hardener, as its overall impact is lower than that of potassium phosphate. The only category this binder lacks is GWP, because of the fact that no carbonation takes place during hardening of the MOC biocomposites. The GWP value could be enhanced by using binder with lower amounts of $MgCl_2$, thus allowing for some parts of MgO to carbonate, but still achieving the necessary high early strength.

4. Discussion

The results obtained are in line with previous LCA research on LHC materials that show CO_2 uptake ranging from 36.08 to 1.6 kg CO_2 eq/FU, as the FU varies among the research (Arrigoni et al., 2017; Boutin et al., 2006; Ip and Miller, 2012; Pretot et al., 2014). The results are summarized in Table 5. It can be seen that GWP balance of lime-based binders used in this paper is similar to those from other studies – ranging from -30.91 to 4.88 kg CO_2 eq/FU. The results from Fig.8 showed that most of this uptake is done by hemp shives, which coincides with results from all other studies in Tab.5. One of the differences lies in the assumptions about CO_2 uptake from lime-based binder. Boutin (Boutin et al., 2006), Ip (Ip and Miller, 2012) and Pretot (Pretot et al., 2014) all consider complete carbonation of the binder, as is done in this paper, Arrigoni (Arrigoni et al., 2017) assumed partial carbonation that was done after 240 days based on experimental results. If total carbonation of binder would be considered, the net balance would be -26.01 kg CO_2 eq/FU instead of 12.09 kg CO_2 eq/FU. Using such partial carbonation approach would lead to considerably different results in this paper and more favorable results for the use of MgO binder.

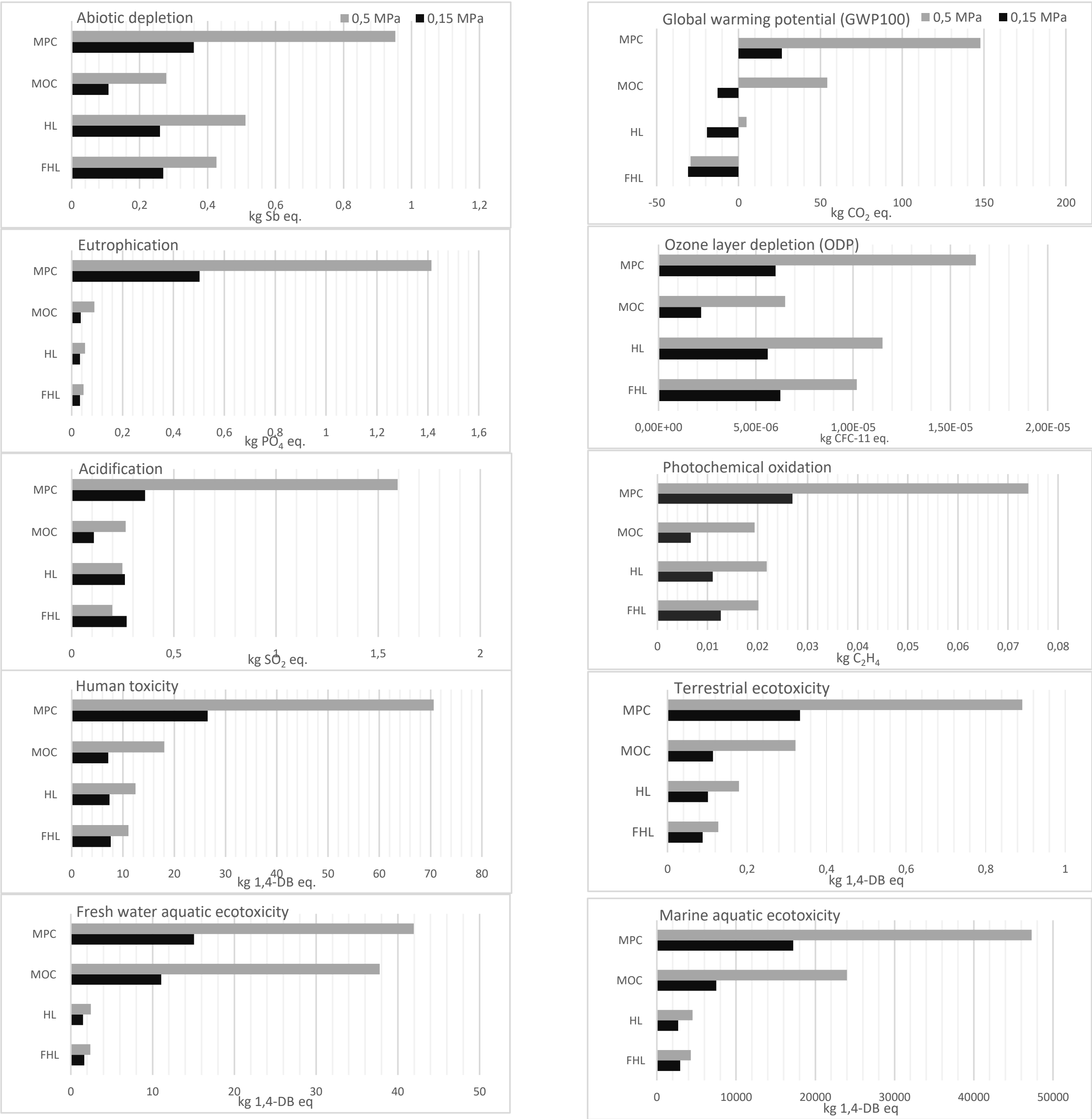


Figure 7 CML2 Baseline results for each impact category

Another aspect of binder comparison is that MgO binders have been claimed to have superior environmental characteristics over lime and cement binders due to lower calcination temperatures of magnesium (Mo and Panesar, 2013) and possibilities of MgO to carbonate, thus sequestering CO_2(Galvez-Martos et al., 2016). However, some studies, which mainly focused on the LCA of MgO production, have found that, comparing only by binder mass, MgO releases more CO_2 than the same amount of cement (Ruan and Unluer, 2016) (Barcelo et al., 2013). This is mainly due to the fact that decomposition of magnesite releases 1.10 t/t CO_2, whereas limestone only 0.78-0.83 t/t CO_2, despite the lower calcination temperatures (Ruan and Unluer, 2016). This directly impacts the GWP potential as can be seen from Table 5 and Figure 8, as magnesium binders have greater contribution to GWP than lime-based binders, although this can be countered by decreased use of binder in MOCs case.

On the other hand, research suggests that a dynamic LCA could be used, when dealing with biogenic CO_2 (from hemp and wood), to achieve more consistent results throughout different research, (Krause, 2017; Levasseur et al., 2013)Although the aim of this research was to compare the different possible binders and their impact on GWP and other categories, which has been achieved.

5. Conclusions

Introduction of magnesium based binders as replacement to lime based binders in biocomposites with hemp has overall proven to be a valuable trial. The MPC and MOC binders have exhibited 3 to 4 times higher compressive strength at similar densities compared

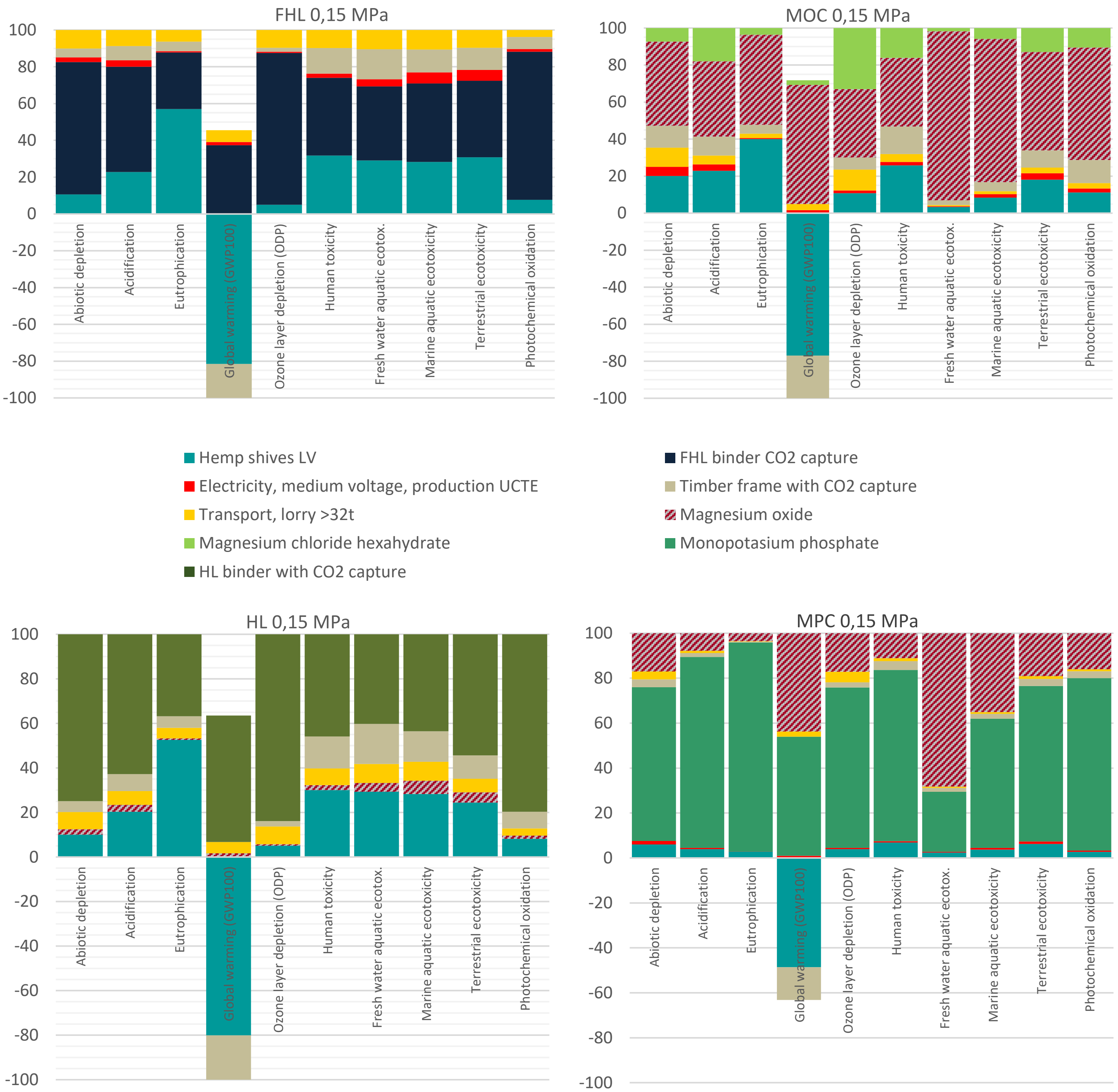


Figure 8 CML2 impact factors for 0.15 MPa wall

Tab.5. GWP comparison with different hempcrete LCA studies

Study/name		Shives, kg	Water, kg	Binder, kg	Thermal conductivity, W/m*K	Density, kg/m^3	Thickness, m	U -value, W/m^2*K	Hemp CO_2 uptake, kg CO_2 eq/kg shives	GHG balance, kg CO_2 eq/FU
(Boutin et al., 2006)		24,8	37,2	54,5	0,109	330	260	0,42	2,105	-35,53
(Ip and Miller, 2012)		30,0	75,0	50	0,057	275	300	0,19	1,527	-36,08
(Pretot et al., 2014)		20,4	67,0	45	0,086	390-460	240	0,36	1,700	-1,60
(Arrigoni et al., 2017)		31,4	58,6	44,5	0,067	330	250	0,27	1,840	-12,09
Present study	MPC(0,15)	43,2	70,6	37,3	0,062	245,2	0,344	0,18	1,84	26.49
	MPC(0,50)	56,0	119,8	106,9	0,080	371,5	0,446	0,18	1,84	147.76
	MOC(0,15)	43,2	54,0	34,0	0,062	210,1	0,344	0,18	1,84	-12.68
	MOC(0,50)	59,5	74,4	121,5	0,085	380,1	0,474	0,18	1,84	54.29
	FHL(0,15)	56,9	129,7	117,2	0,082	368,9	0,453	0,18	1,84	-30.91
	FHL(0,50)	75,4	192,2	195,9	0,108	515,9	0,600	0,18	1,84	--29.33
	HL(0,15)	52,1	103,0	75,8	0,075	322,6	0,415	0,18	1,84	-19.28
	HL(0, 50)	67,9	166,6	163,4	0,097	446,6	0,541	0,18	1,84	4.88

with traditionally used hydraulic lime binders, due to biocompatibility of MgO and higher overall and early strength of MPC and MOC mortars.

Binders have shown varied results regarding LCA. MPC showed highest negative impact in almost all the categories, despite its high strength and density ratio. This was mainly due to its hardener – potassium phosphate which is highly energy and resource intensive. As phosphorus has finite natural reserves and its demand is increasing with rising population levels and growth of food demand (Kataki et al., 2016), it can be concluded that the use of MPC binder for hemp concrete cannot be justified from environmental point of view.

The lime-based binders have shown good overall LCA performance, as their GWP impact was the lowest due to carbonation of lime based binders. Also the experimental FHL binder showed promising results, as it had even higher CO_2 sequestration potential than the traditionally used HL.

MOC had the lowest density for a 0.15 MPa wall, resulting in the lowest material consumption that was one of the reasons for its low impacts in half of the categories. This was also caused by the low environmental impact of $MgCl_2$ – hardener of MOC. Although the binder does not sequester CO_2 in the process, its GWP impact is only 6.60 kg CO_2 eq/FU higher than for HL binder of the 0.15 MPa wall. For more dense materials this difference is larger, as amount of hemp shives stays constant. The overall MOC performance suggests that it should be used in further research.

6. Acknowledgments

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