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# Comparative life cycle assessment of magnesium binders as an alternative for hemp concrete

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ABSTRACT

To counter the negative environmental impact, particularly greenhouse gas emission generated by the construction industry, many low-impact materials are being produced and researched having neutral $CO_2$ emissions and low thermal conductivity. 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 this study alternative magnesium binders are proposed to substitute the traditionally used lime binder in hemp concrete, comparing the environmental impact of these binder composites. To make the comparison, experimental mixtures with both traditionally used and alternative binder composites were produced and their mechanical and thermal properties tested. The magnesium binders showed promising results as these composites were approximately two 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 tested composites. Lime based binder composites achieved negative $CO_2$ emissions, varying from −46.5 to −68.6 kg $CO_2/m^3$. Alternative binder, magnesium phosphate cement, demonstrated significantly greater environmental impact than all other binders due to its hardener, potassium phosphate, which is highly energy and resource intensive. 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. These negative $CO_2$ emissions were achieved with biogenic $CO_2$ uptake from hemp growth and low binder content, thus achieving low thermal conductivity of 0.062 $W/m^2*K$ at 214 $kg/m^3$ density.

## 1. Introduction

In recent years world leaders have signed several agreements committing to limit $CO_2$ emissions, for example the Paris Agreement ratified by the EU in 2016 (UN, 2015). In order to achieve these commitments the EU has several environmental targets − such as the directive EU2010/31/EU aiming at reducing the amount of $CO_2$ emissions by 20% by 2020 (EU, 2010), or the Energy and Climate framework 2030 aiming at reducing the greenhouse gases by 40% and increasing energy efficiency by 27% by 2030 (EU, 2014). 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 used for heating, ventilation and air conditioning (HVAC) due to the insufficient insulation of buildings and production of construction materials (Li et al., 2017; Lin and Liu, 2015).

Additionally, although the Global Warming Potential (GWP) is currently the most topical among the environmental impact factors 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 (Hossain et al., 2018; Sandanayake et al., 2018) such as acidification (Davis et al., 2017; Estokova et al., 2017), eutrophication (Marcelino-Sadaba et al., 2017) and toxicity (Balaguera et al., 2018; Kobetičová and Černý, 2017). It is related to the fact that the building material industry can have considerable impact on the environment due to the significant amount of raw materials consumed (Hossain et al., 2016) (around 3000 Mt/year, more than in any other industry) (Pacheco-Torgal and Labrincha, 2013) and high energy intensity.

To reduce the negative impact of these factors, building materials with both good thermal insulation properties to lower the energy

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consumption for the household HVAC needs and low environmental impact in the production process are necessary (Corscadden et al., 2014; Palumbo et al., 2015). One of the materials meeting these requirements is the lime-hemp concrete (LHC), a bio-based composite material that contains residues from 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 (Pervaiz and Sain, 2003) and lime is sequestering $CO_2$ by hardening through carbonation resulting in a carbon neutral or even negative final material that sequesters from 6.67 to 136.65 kg $CO_2$ eq./$m^3$ (Arrigoni et al., 2017; Ip and Miller, 2012; Pretot et al., 2014; Shea et al., 2012). The material also has good thermal insulation properties ranging between 0.05 and 0.12 W/m*K (Walker et al., 2014), exceptional moisture buffering (Maalouf et al., 2014; Rahim et al., 2015) and acoustic properties (Cérézo, 2005). Additionally, its environmental impact is lower than traditionally used building materials (Pretot et al., 2014).

In the LHC materials hydrated and hydraulic lime is used as a binder, which has relatively low mechanical strength and 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). It is also possible to use it in panel or building block production with increased binder amount, 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 to 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 create 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 in comparison to cement or lime.

Magnesium oxychloride cement (MOC), commonly known as Sorel cement, is non-hydraulic binder. 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 $MgCl_2$, four main crystal reaction phases are created, two of these phases can stably exist in temperatures below 100 °C, namely phase three ($3Mg(OH)_2{\cdot}MgCl_2{\cdot}8H_2O$) and phase five ($5Mg(OH)_2{\cdot}MgCl_2{\cdot}8H_2O$) (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 calcination temperature of reactive MgO is about 700 °C which is lower than for lime. 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 which contain wood fibre and perlite and are covered with glass cloth (Manalo, 2013; Rusthi et al., 2017). 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 ceramic − which is used in this study is based on monopotassium phosphate ($KH_2PO_4$) reaction with dead-burned magnesium oxide, calcined at temperatures above 1500 °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 reach up to 80% of 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 the 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 odour 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 good alternatives for conventional cement and lime binders because of their high strength (Chen et al., 2017), fire resistance (Fang et al., 2018) and compatibility with organic aggregates (Wang et al., 2018).

The goal of the research is to compare bio-based materials with different binders − lime and magnesium based − from their environmental impact perspective. To achieve this, it is necessary to use Life Cycle Assessment (LCA) for calculating both negative and positive environmental impacts of the selected binders. A functional unit that is comparable for all the binders is necessary for the calculation purposes. Consequently, the experimental part of this paper is focused on finding key properties of proposed biocomposites by creating experimental hemp-binder mixtures and testing them. From the results of the experiment, a LCA is conducted, and environmental impacts are obtained and compared for different binder composites.

## 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 ($MgCO_3$). They are both produced in Europe. The dead-burned type M-76 comes from the Slovakian company "Integra Ltd" and it is calcined at temperatures up to 1700 °C, used for MPC binder. Caustic magnesia CCM RKMH-F is provided by the Austrian company "RHI AG Ltd", and is used for MOC binder. Their composition is presented in Table 1.

For hardening of dead-burned magnesia a monopotassium phosphate $KH_2PO_4$ fertiliser (MKP) 0-52-35 supplied by Prayon S.A. was used, with $P_2O_5$ content of at least 51.6%. Magnesium chloride hexahydrate that is made in Germany and contains 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. The first was hydrated lime CL90, made by Lhoist Poland Ltd, and used for experimentally formulated lime binder FHL. The second was hydraulic lime binder, used commercially for the LHC construction, and 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 °C temperature for 40–50 min. 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